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Evaluation of the force constants of non-polar gases from viscosity data

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EVALUATION OF THE FORCE CONSTANTS OF NON-POLAR GASES FROM VISCOSITY DATA

BY

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A

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I. INTRODUCTION

The analytical expressions for the transport coefficients (i.e. viscosity, thermal conductivity, and diffusivity) of an ideal gas can be derived from the kinetic theory of gases. It is also possible to make these analytical expressions adequate for real gases if the intermolecular forces of attraction and repulsion for these gases have been taken into consideration.

The intermolecular forces have been studied by many investigators. The Lennard-Jones potential is one of the most realistic semi-empirical statements which represents particularly the intermolecular forces of attraction and repulsion for non-polar gases.

The values of the Lennard-Jones potential parameters or the force constants of the non-polar gases have been determined from both diffusion and viscosity data. The work of previous investigators have indicated that the values of the force constants determined from diffusion measurements were not always in good agreement with those obtained from viscosity data.

Much of the viscosity data of gases available from the literature have been measured under flow or dynamic conditions. The purpose of this research was

not only to determine the actual viscosities of a few non-polar gases at three temperature levels by means of a rolling viscometer, but also to demonstrate that this method was accurate enough to determine the Lennard-Jones force constants for the gases used. In addition, the calculated force constants were to be used to determine viscosities, self-diffusion coefficients of single gases and diffusivities of binary pairs at various other temperatures and compared with actual experimental data and literature values. If the above could be accomplished satisfactorily, the work could be extended to determine the force constants, viscosities, and diffusivities of non-polar gaseous mixtures.

The gases used in this investigation, in addition to air, which was used to calibrate the viscometer, were argon, helium, carbon dioxide, oxygen, nitrogen and hydrogen.

II. LITERATURE REVIEW

Intermolecular Forces of Non-Polar Gases

It is known that molecules attract each other when they are a certain distance apart and repel each other when they come close together. The force of interaction (F) between two spherical non-polar molecules is a function of the intermolecular distance (r). It is more convenient to use the potential energy of interaction $\phi(r)$ rather than the force of interaction.

The potential energy function $\phi(r)$ is defined as follows:

$$F(r) = -\frac{d\phi}{dr} \quad ; \quad \text{and} \quad \phi(r) = \int_r^\infty F(r)dr$$

where F = intermolecular forces between two spherical non-polar molecules.

r = intermolecular separation

$\phi(r)$ = potential energy of interaction.

Development of the Potential Energy Function. The intermolecular forces of gases can be represented by various empirical potential functions. Several of these

empirical functions have been described by Hirschfelder, Curtiss and Bird [1] in detail. The distinguishing characteristics of these functions are described briefly as follows:

Rigid Elastic Spheres. This function represents a rigid elastic sphere of diameter σ, and the values of the potential can be represented as follows:

$$\begin{aligned} \phi(r) &= \infty \qquad r < \sigma \\ \phi(r) &= 0 \qquad r > \sigma \end{aligned} \tag{2}$$

Figure 1 is a pictorial representation of some of these empirical potential functions.

Point Centers of Repulsion. The potential represented by the following equation:

$$\phi(r) = ur^{-v} \tag{3}$$

where u = a constant
v = index of repulsion

The Sutherland Model. This is represented by the equations:

$$\begin{aligned} \phi(r) &= \infty \qquad r < \sigma \\ \phi(r) &= -ur^{-\beta} \qquad r > \sigma \end{aligned} \tag{4}$$

where , u = constants

β = diameter of the riged sperical molecule

This model is also found to be a fairly realistic model for use.

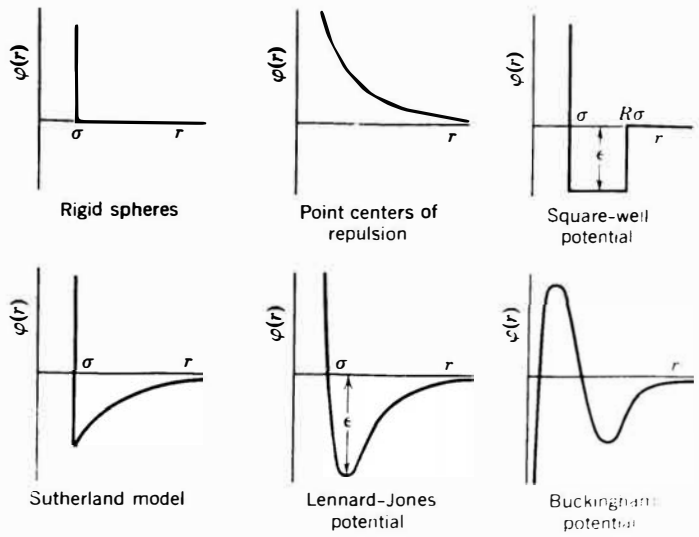


Figure 1. Spherically Symmetrical Potential Functions

Hirschfelder, Joseph O., Charles F. Curtiss and R. Byron Bird: "Molecular Theory of Gases and Liquids," p. 30. John Wiley and Sons, New York, N. Y., 1954.

Square Well Potential. The square well potential may be represented mathematically as follows:

$$\begin{aligned} \phi(r) &= \infty & r &< \sigma \\ \phi(r) &= -\epsilon & \sigma &< r < R\sigma \\ \phi(r) &= 0 & r &> R\sigma \end{aligned} \qquad (5)$$

Both attractive and repulsive forces are considered in this model. This model has been found very useful in calculations involving complex molecules as the three adjustable parameters allow for considerable lattitude.

Lennard-Jones Potential. This potential is expressed as follows:

$$\phi(r) = 4\epsilon \left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6} \right] \qquad (6)$$

where ϵ = maximum energy of attraction

σ = collision diameter or value of r for which $\phi(r) = 0$

r = separation between the molecules.

The inverse sixth power term is the energy of attraction, and the inverse twelfth power term represents the repulsive interaction between the molecules. This potential function has been very satisfactory in predicting the intermolecular forces for non-polar gases. The parameters σ and ϵ, which have dimensions of length and energy respectively, are constants characteristic of the chemical species only. They are called the force constants of a gas. The Lennard-Jones potential has been chosen in

this research as the potential energy function or the assumed mathematical model from which the force constants for the six non-polar gases were calculated.

The Buckingham Potential. The Buckingham potential is a four-parameter function. It may be represented mathematically as follows:

$$\phi(r) = v \exp(-ur) - w^{-6} - w'r^{-8} \qquad (7)$$

where u, v, w and w′= constants.

A modified form of this potential is more realistic than the Lennard-Jones potential, but is very difficult to handle numerically.

Calculation of Transport Coefficients for Non-Polar Gases.

Hirschfelder, Curtiss and Bird [2] present the equations for calculation of the first approximation of the transport coefficients of pure gases as follows:

$$\mu \times 10^7 = 266.93 \frac{\sqrt{MT}}{\sigma^2 \Omega^{(2)}(T^*)} \qquad (10)$$

$$D = 0.002628 \frac{\sqrt{T^3/M}}{(P)\sigma^2 \Omega^{(1)}(T^*)} \qquad (11)$$

$$\gamma \times 10^7 = 1981.1 \frac{\sqrt{T/M}}{\sigma^2 \Omega^{(2)}(T^*)} \qquad (12)$$

where μ = viscosity, gm/cm-sec

D = coefficient of self-diffusion, cm^2/sec

γ = thermal conductivity, $^{cal}/_{cm\text{-}sec\text{-}°K}$

P = pressure, atm

T = temperature, °K

M = molecular weight, gm

σ = collision diameter, Å

T^* = reduced temperature defined as KT/ϵ

$\Omega^{(1)}_{(T^*)}$ = collision integral at T^* for diffusion coefficient, a function of the parameter $T^* = \frac{KT}{\epsilon}$

$\Omega^{(2)}_{(T^*)}$ = collision integral at T^* for viscosity and thermal conductivity, a function of the parameter $T^* = \frac{KT}{\epsilon}$

The coefficient of diffusion in a binary mixture can be expressed as follows:

$$D_{12} = 0.002628 \frac{\sqrt{T^3(M_1 + M_2)/2M_1M_2}}{(P)\sigma_{12}^2 \Omega^{(1)}_{(T_{12}^*)}} \qquad (13)$$

where D_{12} = diffusion coefficient, cm^2/sec

M_1, M_2 = molecular weights of species 1 and 2, gm

T_{12}^* = KT/ϵ_{12}

P = Pressure, atm

σ_{12} = collision diameter of the binary mixture

= $1/2\ (\sigma_1 + \sigma_2)$,

$\Omega^{(1)}(T^*_{12})$ = collision integral, a function of $T^*_{12} = \frac{KT}{\epsilon}$

The higher approximations to those transport coefficients are given by

$$\mu_k = \mu f_n^{(k)} \tag{14}$$

$$D_k = D f_D^{(k)} \tag{15}$$

$$\gamma_k = \gamma f^{(k)} \tag{16}$$

$$D_{12\ k} = D_{12}\ f_{D12}^{(k)}$$

The functions $f^{(k)}$, $f_D^{(k)}$, $f^{(k)}$ and $f_{D12}^{(k)}$ differ but slightly from unity and vary slightly with reduced temperature (T^*).

Determination of Force Constants from Diffusion Data.

The force constants can be calculated from the experimental diffusion coefficient by using Equation (13). The values of the collision integral $\Omega^{(1)}(T^*)$ have been evaluated and tabulated [3] for various reduced temperatures (T^*). It is interesting to note that the values of the force constants obtained from diffusion coefficients are not always the same as those determined from viscosity data.

Determination of Force Constants from Viscosity Data. The function $\Omega^{(2)}$ (T*) has been computed and tabulated [4] by Bird for various reduced temperatures (T^*). The force constants can be calculated from the experimental viscosity data at different temperature levels using Equation (10).

Measurement of Viscosity of Gases

Several methods have been developed for the determination of viscosity data for gases. These methods are described very briefly as follows:

Capillary Flow Method. [5] A common method for the determination of gaseous viscosities requires measuring the quantity of the gas that will flow through a capillary tube of known cross sectional area during a specific time period. These physical measurements can be mathematically related to the viscosity.

Ultrasonic Vibration Method. [6] This method has been developed for fluid viscosity using ultrasonic vibrations. This method provides an instaneous and continuous viscosity measurement using ultra-high frequency sound waves. The viscosity of the fluid is determined by the vibration rate of a steel blade which has been immersed in the fluid.

Oscillating Disk Method. [7,8] In this method a circular disk is suspended in the gas horizontally and is given a small torsional oscillation in its own plane. The rate at which the oscillations diminish measures the viscosity of the surrounding gas. The disk is suspended between two disks of the same material in order to increase the viscous drag. The oscillation amplitude can be measured by optical means.

Rotating Cylinder Method. This is a modification of the oscillating disk method. [9, 10, 11] The oscillating disk has been replaced by rotating concentric cylinders. This method has been used by many investigators for the determination of gaseous viscosity. The inner cylinder is driven at a constant speed by a drive motor while the outer cylinder is suspended in the gas from a small torsional wire. When the inner cylinder is in motion, the viscous action of the gas between the cylinders causes an oscillation of the outer cylinder. By measuring the oscillation amplitude and time for completing one cycle, the viscosity of the gas can be determined.

Rolling Ball Viscometer. A more recent development in laboratory type viscometers is the rolling ball viscometer. In this method, a ball of known diameter is allowed to roll through an inclined precision bore tube which is filled with the gas to be tested. The time required for the ball to traverse a specific distance may

be used to determine the viscosity of the gas. Hubbard and Brown [12] indicated that this instrument could be used to determine the viscosity of a gas accurately when the fluid flow around the rolling ball was in the streamline flow region. In using this method, the instrument is standardized with a fluid of known viscosity. The advantage of this method is that only two variables are involved - - roll time of the ball and the inclination angle of the viscometer tube. There are no other correction factors to be applied as in other methods of viscosity determinations.

III. EXPERIMENTAL

The experimental section of this thesis is composed of the following parts: (1) purpose of investigation; (2) plan of experimentation; (3) materials; (4) apparatus; (5) method of procedure; (6) results; (7) sample calculations.

Purpose of Investigation.

The purpose of this research was not only to determine the actual viscosities of a few non-polar gases at three temperature levels by means of a rolling viscometer, but also to demonstrate that this method was accurate enough to determine the Lennard-Jones force constants for the gases used. In addition, the calculated force constants were to be used to determine viscosities, self-diffusion coefficients of single gases and diffusivities of binary pairs at various other temperatures and compared with actual experimental data and literature values. If the above could be accomplished satisfactorily, the work could be extended to determine the force constants, viscosities, and diffusivities of non-polar gaseous mixtures.

The gases used in this investigation, in addition to air, which was used to calibrate the viscometer, were argon, helium, carbon dioxide, oxygen, nitrogen and hydrogen.

Plan of Experimentation.

The plan for the accomplishment of the work entailed in this thesis was composed of four steps: (1) choice of a method for viscosity measurements, (2) design of equipment, (3) measurement of viscosity, (4) calculation of viscosity, and (5) calculation of force constants and transport coefficients.

Choice of a Method for Viscosity Measurements. Various methods were available for the determination of the viscosity of gases. The rolling ball method which has been developed and correlated by Hubbard and Brown [12] was chosen because of the following reasons: (1) the apparatus was extremely simple, (2) only a small sample was required, and (3) the procedure of measurement was simple and rapid.

Design of Equipment. The design of the rolling ball viscometer was based on the method developed by Hubbard and Brown [12]. The viscometer was designed to allow the gas within the viscometer tube to be maintained at constant temperatures of 5, 50 and 90 degrees Centigrade. The time required for the ball to travel the distance in the viscometer tube was recorded precisely by a photoelectric timing system.

Measurement of Viscosities. The measurement of the viscosities of the different gases involved a series of

tests at three constant temperature levels. Measurements were taken in such a manner that the angle of inclination was kept constant at each temperature level. The viscosity of air was used as a standard to calibrate the viscometer.

Calculation of Viscosities. This calculation followed the method developed by Hubbard and Brown, [12] and utilized successfully by Kiyama and Makita. [13]

Calculation of Force Constants and Transport Coefficients. The method presented by Hirschfelder, Curtiss and Bird [14] was used to evaluate the force constants and the transport coefficients. All calculations are illustrated in the sample calculation sections of this thesis.

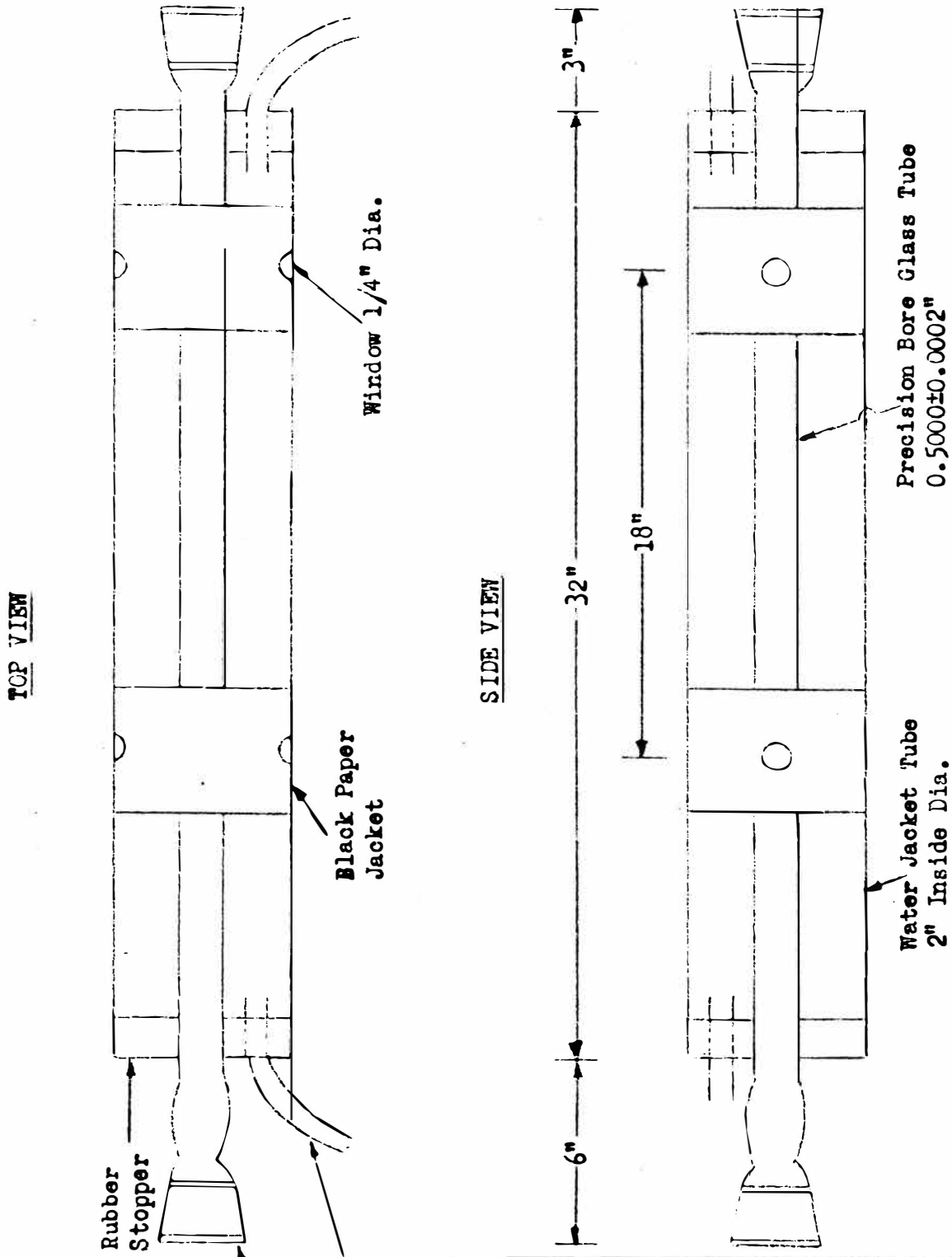
Materials.

All the material used in the experimental work are listed and described in Appendix A.

Apparatus.

The apparatus is described as follows:

Viscometer Tube. The viscometer tube used for the experimental work is illustrated in Fig. 2 and Fig. 6. This viscometer tube consisted of a precision bore gas tube of 0.50 $\pm$ .0002 inch inside diameter and a standard



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VISCOMETER TUBE

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constant temperature water jacket tube of 2.0 inch inside diameter.

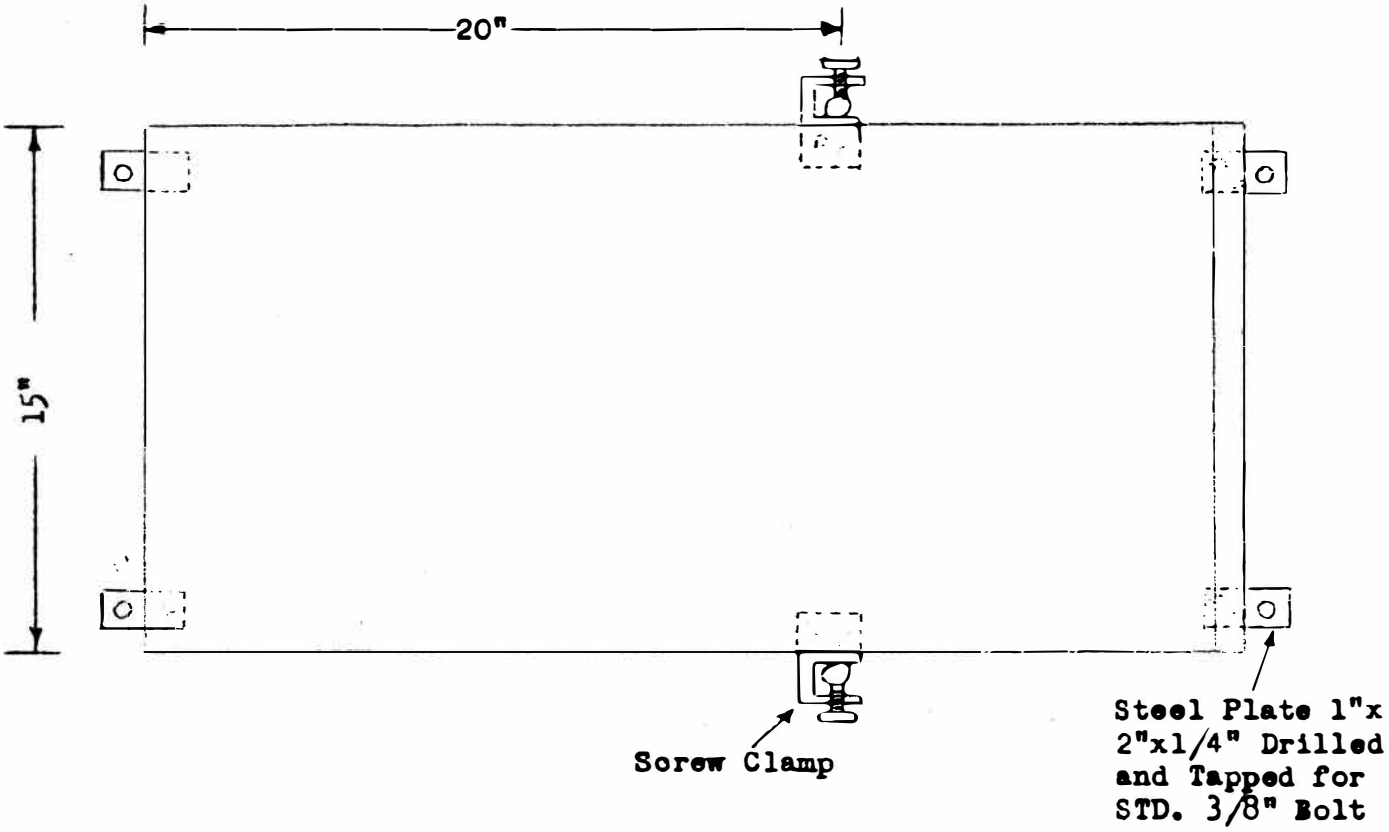
Viscometer Mounting Board. The mounting board was designed such that the viscometer tube could be elevated to any desired angle. Two 30" x 15" x 3/4" plywood boards were hinged together so that the base board could be kept at a constant level while the upper board could be elevated by two side clamps to any desired angle of inclination from the horizontal. This is shown in Fig. 3 and Fig. 7.

Rolling Ball. The ball used for this viscometer was a spherical steel ball with a diameter of 0.4964 $\pm$ 0.0002 inches.

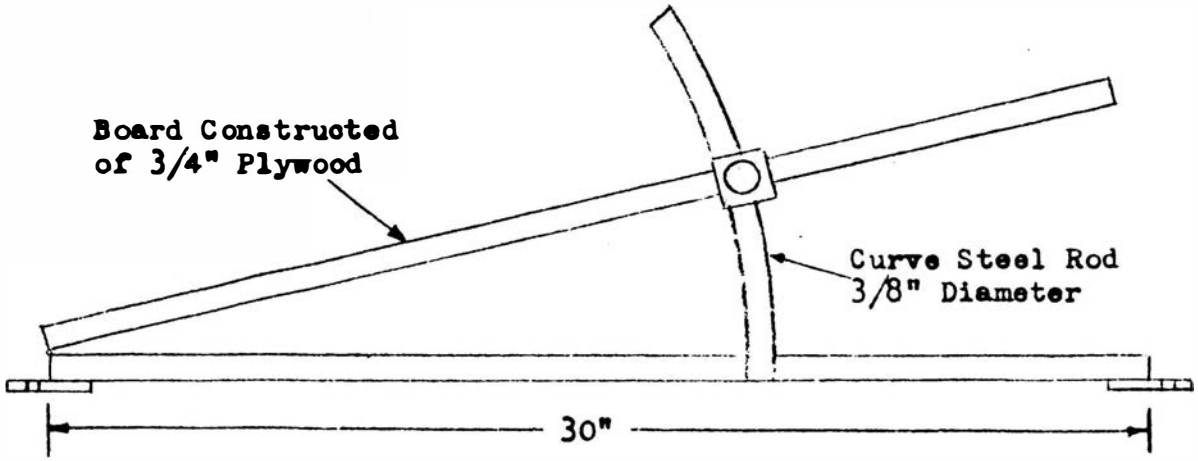
Electric Timer. The time for the ball to traverse the distance between the two photoelectric receivers was measured by a "Standard" type precision electric timer. It could be read to 0.01 second and estimated to 0.005 second. Since this timer was operated by a 24 volt direct current, a rectifier was necessary to convert the 110 V AC to 24 V DC.

Rectifier. The rectifier was specially designed and constructed for operating the precision electric timer. The input and output of the rectifier was 110 V AC and 24 V DC respectively. The rectifier has been shown in Fig. 4 and Fig. 7.

TOP VIEW



SIDE VIEW



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VISCOMETER MOUNTING BOARD

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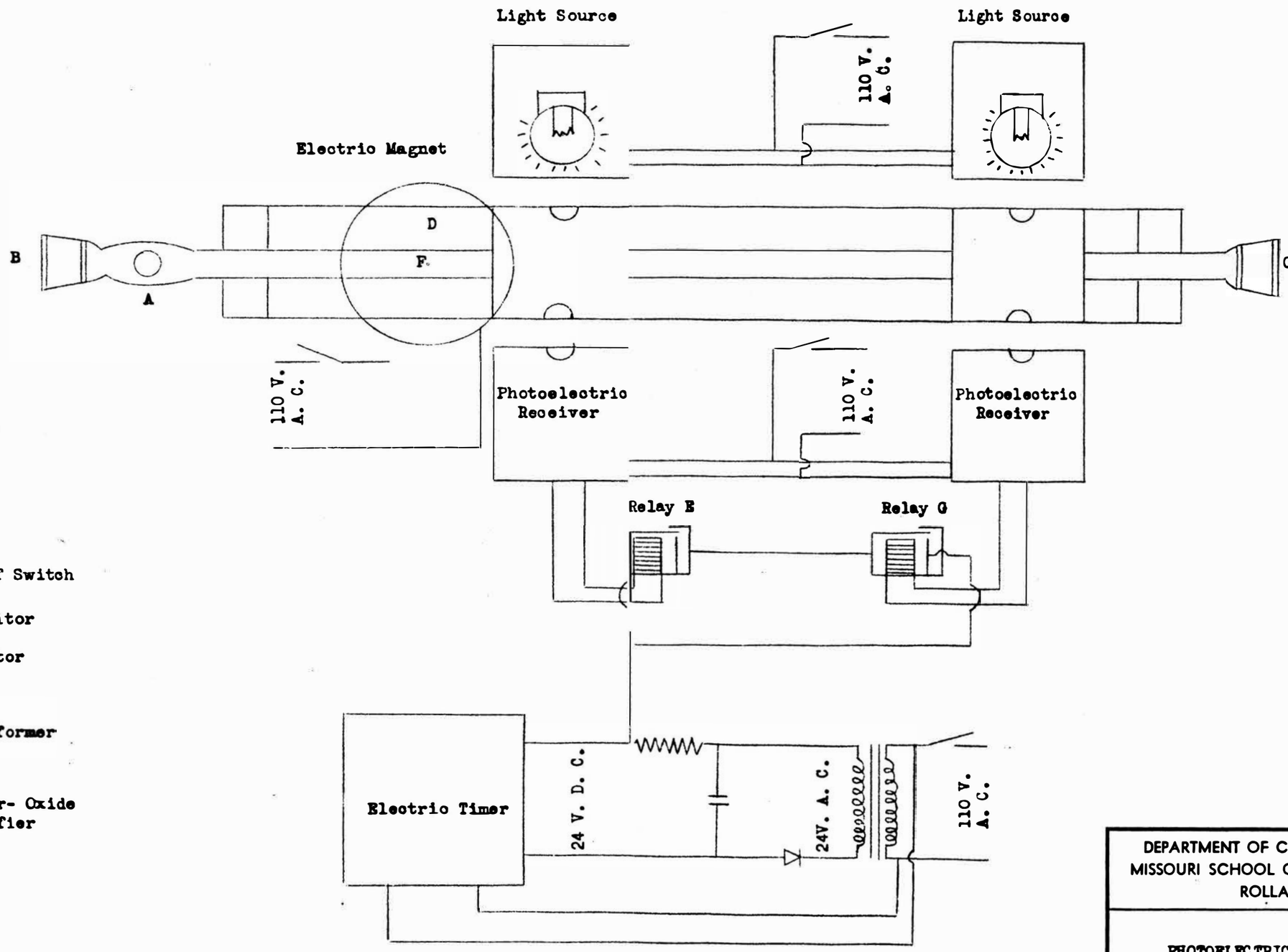
Time Measurement Devices. The time required for the steel ball to traverse the distance in the viscometer tube was recorded precisely by the use of a photoelectric timing system and is illustrated in Fig. 4 and Fig. 6. The system consisted of two photoelectric receivers, two light sources, two sensitive relays, a rectifier and a precision electric timer. The breaking of a beam of light by the passage of the steel ball in the viscometer tube actuated the relays which were connected to the rectifier and the precision electric timer. Thus the time for the ball to roll the distance between the two photoelectric receivers could be recorded automatically.

Temperature Controlling System. The temperature of the gas in the viscometer tube was held constant at 5 ± 0.15, 50 ± 0.15 and 90 ± 0.2 degrees centigrade by using a constant temperature water bath. The water bath container was a five gallon glass vessel. A pump was used to circulate the water through the constant temperature water jacket of the viscometer tube. The temperature of the water bath was controlled by a "Micro Set Thermoregulator" and a 1,000 watt water heater. It has been shown in Fig. 7.

Stopcocks. Two stopcocks were used in this viscometer. A straight stopcock with rubber stopper was attached to the upper end of the viscometer tube for the control



On-Off Switch

Capacitor

Resistor

Transformer

Copper- Oxide Rectifier

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PHOTOELECTRIC TIMING SYSTEM

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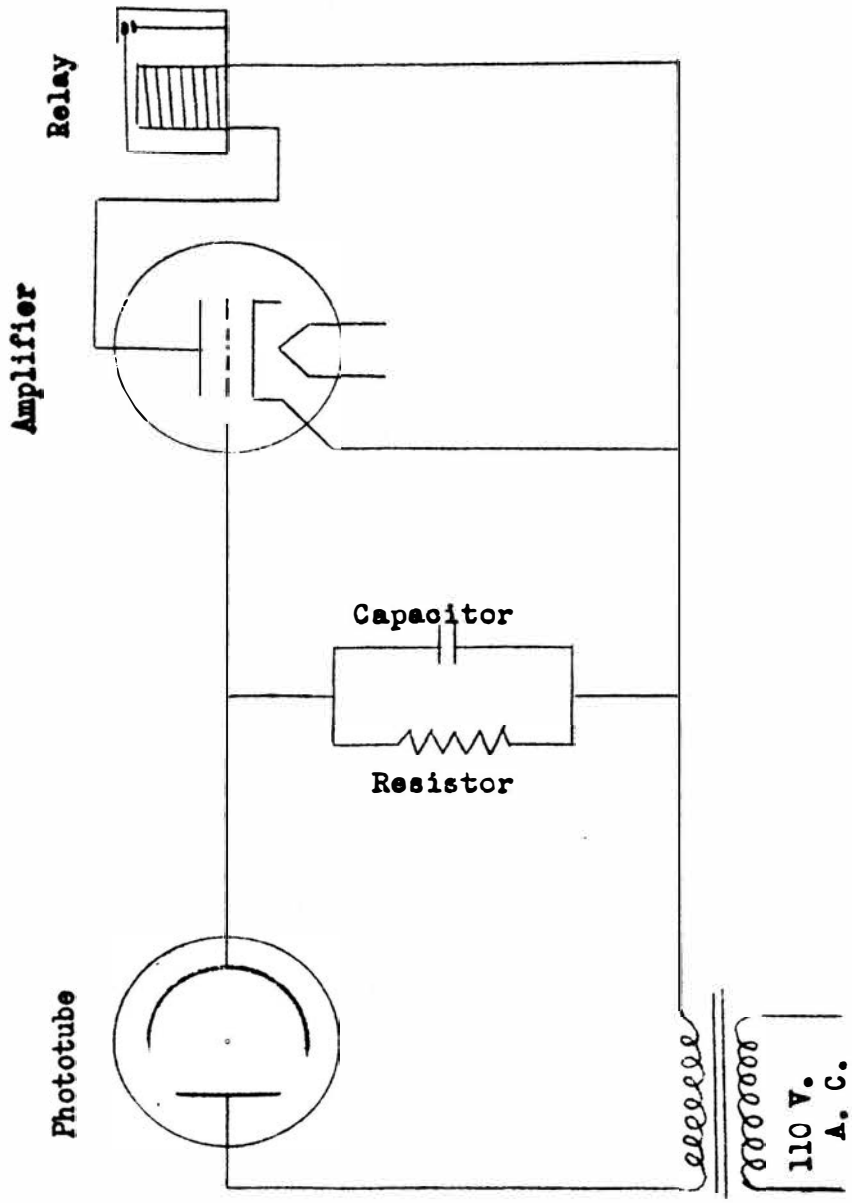

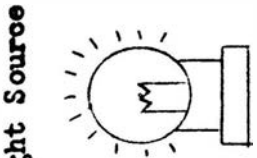

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PHOTOELECTRIC RECEIVER

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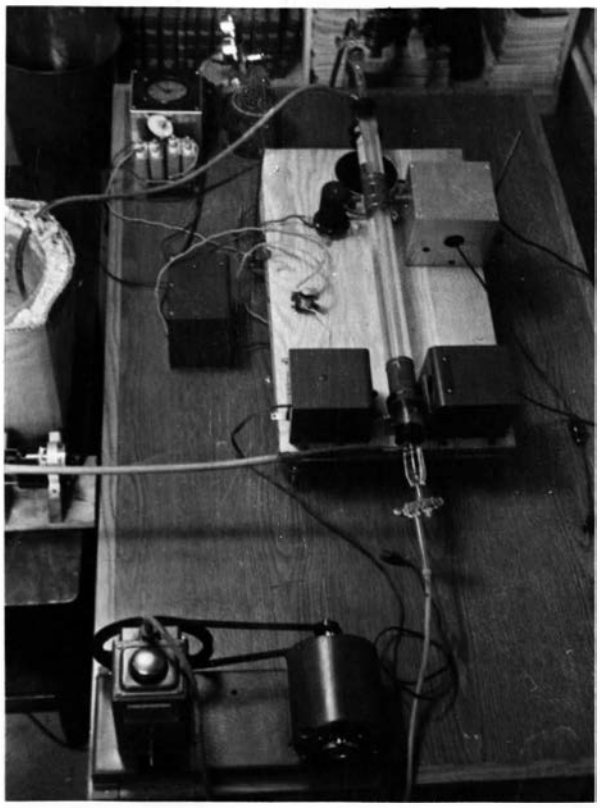

Figure 6. Apparatus Showing Viscometer Tube and Components.

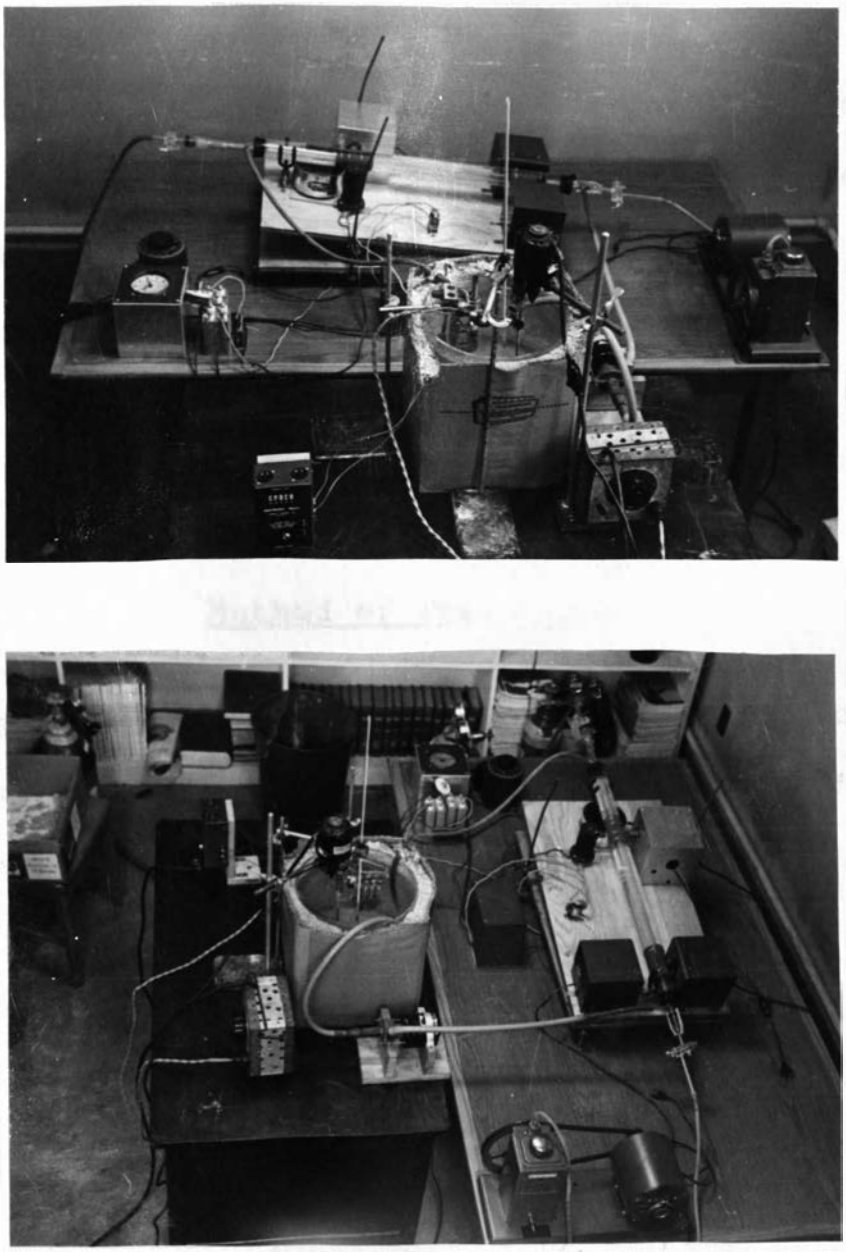

Figure 7. General View of the Apparatus.

of the gas entry into the tube, and a three-way stopcock with two tubes on one side was attached to the lower end of the viscometer tube as shown in Fig. 7. One of these stopcock tubes was connected to a vacuum pump, whereas the other tube was used as a vent valve to the atmosphere to release the extra pressure in the viscometer tube.

Vacuum Pump. A "Cenco-Hyvac" type vacuum pump was used to evacuate the viscometer tube prior to the introduction of the gas to be studied.

Method of Procedure.

Determination of Viscosities. In this experimental work, the viscosity of air was chosen to standardize the viscometer. The viscosity for a gas has been calculated (12, 13, 15) using the following equation for the rolling ball viscometer:

$$\mu = bZ \sin \theta \ (\rho_o - \rho) \qquad (17)$$

where μ = viscosity of a gas, gm/cm-sec

b = instrument constant, cm^2/sec^2

Z = roll time, sec

θ = angle of inclination of the viscometer tube, deg

ρ_o = density of the ball, in gm/cm^3

ρ = density of the gas, in gm/cm^3

Equation (17) is applicable only when the flow of gas through the crescent shaped area between the tube and the

ball is in the streamline flow region. If air is used to standardize the viscometer;

$$\mu_{air} = b\, Z_{air} \sin\theta (\rho_o - \rho_{air}) \qquad (17\text{-a})$$

If O_2 is used at the same temperature and the same inclination angle as air,

$$\mu_{02} = b\, Z_{02} \sin\theta\, (\rho_o - \rho_{02}) \qquad (17\text{-b})$$

Dividing Equation (17-a) by Equation (17-b) gives:

$$\frac{\mu_{air}}{\mu_{02}} = \frac{Z_{air}}{Z_{02}} \frac{(\rho_o - \rho_{air})}{(\rho_o - \rho_{02})} \qquad (18)$$

Since ρ_o is much greater than ρ_{air} or ρ_{02},

$$(\rho_o - \rho_{air}) \doteq (\rho_o - \rho_{02})$$

and hence:

$$\frac{\mu_{air}}{\mu_{02}} = \frac{Z_{air}}{Z_{02}} \qquad (19)$$

Viscosity measurements were performed at three temperature levels of 5, 50, and 90 degrees centigrade. Twenty measurements were made for each gas at each temperature level using a constant inclination angle for all the gases. The viscosity was calculated by Equation (19).

Calibration of Viscometer. It was necessary to know whether the gas in the viscometer was in the streamline flow before using Equation (19). Hubbard and Brown (12) demonstrated a correlation between the resistance

factor and the Reynold's number when the ball is rolling at uniform velocity. The resistance factor is defined by the following equation:

$$\text{Resistance factor} = \frac{5\pi g}{42} \times \frac{(D+d)^2}{L^2 d} \times \frac{\rho_o - \rho}{\rho} \times Z^2 \sin\theta \quad (20)$$

The corresponding Reynold's number is calculated from the following equation:

$$\text{Reynold's number} = \frac{Ld^2}{(D+d)} \times \frac{\rho}{\mu Z} \quad (21)$$

where g = acceleration of gravity, cm/sec^2

D = diameter of the tube, cm

d = diameter of the ball, cm

L = distance of roll, cm

ρ_o = density of the ball, gm/liter

ρ = density of the gas, gm/liter

Z = time of roll over distance L, sec

θ = angle of tube inclination, deg

μ = viscosity of the gas, gm/cm-sec

The resistance factor plotted against the Reynold's number on a logarithmic scale should yield a straight line with a slope of -1.0 when the flow is in the streamline region. This line is no longer straight where flow is changing from streamline to turbulent flow.

Correlation Curve Determination. The viscosity of air was chosen as a standard to calibrate the viscometer.

The viscosity of air was taken to be $1,834 \times 10^{-7}$ [16] grams per centimeter per second at 25°C and one atmosphere. The viscometer was filled with air and the roll time of the ball at each angle was recorded. The resistance factor and the Reynold's number were then calculated from the roll time for each inclination angle using Equations (20) and (21). Eight different inclination angles were used in this calibration. The values of the resistant factor were plotted against the corresponding values of the Reynold's number on a logarithmic scale which yielded a straight line with a slope of -1.0 as shown in Fig. 8. For the viscosity measurement of an unknown gas, the inclination angle should be chosen in such a way that the Reynold's numbers and the resistance factors for both the gas and air should fall on the straight line of the correlation curve of Fig. 8, otherwise they are not in the streamline flow region and another inclination angle must be chosen.

Calculation of Force Constants. The values of the Lennard-Jones force constants (ϵ/K) and (δ) were calculated from the experimental viscosity data in the manner outlined by Herschfelder, Curtiss and Bird [14]. From Equation (10) and Equation (14), the third approximation of the viscosity of a gas at T_1 is:

$$\mu(T_1) = \frac{266.93 \sqrt{M T_1} \; f_\mu^{(3)}(T_1^*)}{\delta^2 \Omega^{(2)}(T_1^*)} \qquad (23)$$

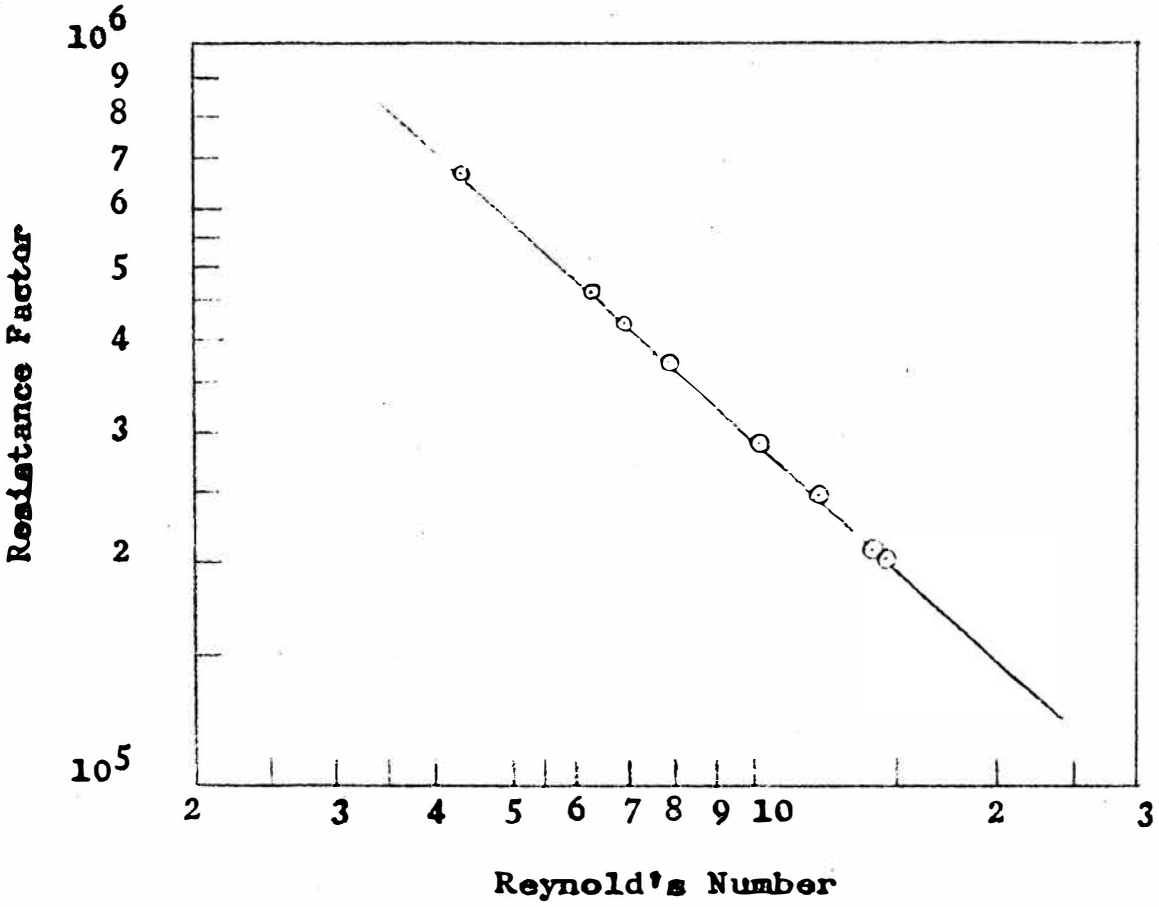

Figure 8. Resistance Factor vs. Reynold's Number Correlation with Air at 25°C.

At another temperature T_2 for the same gas:

$$\mu(T_2) = \frac{266.93\sqrt{M\,T_2}\; f_\mu^{(3)}(T_2^*)}{\sigma^2 \Omega^{(2)}(T_2^*)} \qquad (24)$$

Dividing Equation (24) by Equation (23) gives:

$$\frac{\mu(T_2)}{\mu(T_1)} = \sqrt{\frac{T_2}{T_1}}\; \frac{\Omega^{(2)}(T_1^*)\;\; f_\mu^{(3)}(T_2^*)}{\Omega^{(2)}(T_2^*)\;\; f_\mu^{(3)}(T_1^*)} \quad \text{or}$$

$$\frac{\mu(T_2)}{\mu(T_1)}\;\frac{T_1}{T_2}^{0.5} = \frac{\Omega^{(2)}(T_1^*)\;\; f_\mu^{(3)}(T_2^*)}{\Omega^{(2)}(T_2^*)\;\; f_\mu^{(3)}(T_1^*)} \qquad (25)$$

where $\mu(T_1)$, $\mu(T_2)$ = experimental viscosity data at temperatures T_1, T_2 respectively

T_1^*, T_2^* = reduced temperatures or KT_1/ϵ, KT_2/ϵ

$\Omega^{(2)}(T_1^*)$, $\Omega^{(2)}(T^*)$ = collision integrals for T_1^* and T_2^*

$f_\mu^{(3)}(T_1^*)$, $f_\mu^{(3)}(T_2^*)$ = functions for calculating the third approximation for the viscosity data at T_1^*, T_2^* respectively

The values for the collision integrals and $f_\mu^{(3)}(T^*)$ at various reduced temperatures have been calculated and tabulated.[3, 4] If the experimental viscosities $\mu(T_1)$ and $\mu(T_2)$ for a non-polar gas are known one of the force constants ϵ/K can be calculated using Equation (25) by a trial and error method.

Calculation of the Collision Diameter. Once the value of ϵ/K is determined, the other force constant of the gas is evaluated directly as follows:

$$\sigma^2 = \frac{266.93 \sqrt{M T_1} f_\mu^{(3)}(T_1^*)}{[(T_1) \times 10^7] \Omega^{(2)}(T_1^*)} \qquad (26)$$

Calculation of the Transport Coefficients. The diffusivity, viscosity and the thermal conductivity for non-polar gases can be calculated from their force constants using Equations (10), (11), (12), and (13).

Procedure for Starting the Viscometer.

1. The steel ball was first placed in the viscometer tube. The ball should be placed in the flanged portion (A) of the viscometer tube.

2. The viscometer was then attached to the gas source. The gas outlet from the cylinder was regulated by a "Matheson Two Stage" automatic gas regulator. The delivery pressure should be adjusted to about two pounds per square inch gage.

3. The viscometer tube was next evacuated by using a vacuum pump. Stopcock B was adjusted so that the sys-

tem back to the gas regulator was under vacuum. After the system was completely evacuated, stopcock C was closed and the gas was admitted to the viscometer tube.

4. The electric magnet D was then turned on and the ball brought from the flanged portion A into the precision viscometer tube at its initial position F.

5. The thermoregulator of the constant temperature bath was adjusted to the desired control temperature and the circulating pump started.

Procedure for Making Observations.

1. After the gas and the ball in the viscometer tube have reached the desired constant temperature, the two light sources and the two photoelectric receivers were turned on.

2. The two relays E and G were then set to a close position manually, and the electric timer and the rectifier turned on.

3. After the electric magnet was turned off, the ball was started rolling down the precision bore viscometer tube.

4. After the roll time was automatically recorded by the electric timer, the rectifier was turned off.

5. The ball was then brought back from the lower end to the upper end of the inclined viscometer tube using the permanent magnet. Thus the ball was brought back to its initial position F.

6. In order to change the gas in the tube, the ball must be positioned in the flanged portion A of the tube by means of the magnet before evacuating the system and admitting a different gas to the viscometer tube.

Procedure for Shutting Down the Viscometer.

1. Turn off the light sources and the photo-electric receivers.

2. Turn off the motor of the electric timer.

3. Turn off the thermoregulator of the water bath and the circulating pump.

Data and Results.

The viscosities for the six non-polar gases, argon, helium, carbon dioxide, oxygen, hydrogen and nitrogen were determined at three temperatures of 5, 50 and 90 degrees centigrade.

The experimental values for the viscosities are presented in Table I. All the viscosities are based on measurements at a pressure of approximately one atmosphere.

The force constants for each gas were evaluated from the experimental viscosity data. The calculated force constants are presented in Table II.

The coefficients of diffusion for gas pairs, the

self-diffusion coefficients and the viscosities for each gas at various temperatures were also calculated from the force constants as shown in Tables III, IV and V.

TABLE I

Experimental Viscosities of
Argon, Helium, Carbon Dioxide, Oxygen
Hydrogen and Nitrogen at 1 Atmosphere

Gas	Temperature (°C)	Viscosity $x10^7$ (gm/cm - sec)
Air*	5.0	1,741
	50.0	1,951
	90.0	2,131.5
Argon	5.0	2,116±6.6
	50.0	2,393±6.2
	90.0	2,625±6.7
Helium	5.0	1,869±6.1
	50.0	2,064±5.8
	90.0	2,223±6.7
Carbon Dioxide	5.0	1,417±5.1
	50.0	1,617±5.5
	90.0	1,806±5.3
Oxygen	5.0	1,927±7.3
	50.0	2,168±7.5
	90.0	2,370±10.3
Hydrogen	5.0	862±3.2
	50.0	950±4.5
	90.0	1,025±5.0
Nitrogen	5.0	1,684±6.8
	50.0	1,880±6.5
	90.0	2,046±10

* Obtained from literature source and used in calibrating the viscometer. Refer to footnote (16).

TABLE II

Lennard-Jones Potential Parameters for Air, Argon, Helium, Carbon Dioxide, Oxygen, Hydrogen and Nitrogen over Various Temperatures Ranges

Gas	Temperature Range ^{o}C	Force Constant ϵ/K ^{o}K	Collision Diameter σ in $\mathring{A}$
Air	5.0 to 50.0	103	
	50.0 to 90.0	104	
	5.0 to 90.0	100.5	3.606
Argon	5.0 to 50.0	126±5	
	50.0 to 90.0	130±6	
	5.0 to 90.0	128±5	3.4123±0.021
Helium	5.0 to 50.0	9.6±1.0	
	50.0 to 90.0	11.6±1.2	
	5.0 to 90.0	10.7±1.1	2.5865±0.022
Carbon Dioxide	5.0 to 50.0	197±5.8	
	50.0 to 90.0	194±6.5	
	5.0 to 90.0	200±6	3.9319±0.03
Oxygen	5.0 to 50.0	116±7	
	50.0 to 90.0	114±7.5	
	5.0 to 90.0	110±7.5	3.467±0.035
Hydrogen	5.0 to 50.0	35.2±3	
	50.0 to 90.0	35.8±3.3	
	5.0 to 90.0	35±3.05	2.9402±0.021
Nitrogen	5.0 to 50.0	86.2±6.4	
	50.0 to 90.0	84.8±7.2	
	5.0 to 90.0	84.3±6.9	3.722±0.034

TABLE III

Calculated Self-Diffusion Coefficients for Argon, Helium, Carbon Dioxide, Oxygen, Hydrogen and Nitrogen at 1 Atmosphere

Gas	T_o (K)	D (cm^2 sec^{-1})
A	353.2	0.247
	273.2	0.156
	77.7	0.01335
H_2	273.0	1.255
	85.0	0.1683
N_2	353.2	0.274
	273.2	0.175
	77.7	0.0163
O_2	353.2	0.2785
	273.2	0.174
	77.7	0.0154
CO_2	362.6	0.156
	273.2	0.0915
	194.8	0.0475

TABLE IV

Calculated Viscosities for Argon, Helium, Carbon Dioxide Oxygen, Hydrogen and Nitrogen at High Temperatures

$x10^7$ in gm/cm-sec

T^oK	A	H	CO_2	O_2	H_2	N_2
500	3,337	2,736	2,350	2,990	1,251	2,554
800	4,629	3,709	3,356	4,120	1,709	3,498
1,000	5,370	4,285	3,930	4,781	1,976	4,016
1,200	6,071	4,795	4,450	5,366	2,223	4,506
1,500	6,973	5,506	5,170	5,967	2,569	5,225

TABLE V(a)

Calculated Diffusion Coefficients for Binary Gas Mixtures at 1 Atmosphere

Gas Pair	σ_{12} (Å)	ε_{12}/K (K)	T (K)	D_{12} ($cm^2\ sec^{-1}$)
He - Air	3.096	32.79	276.2	0.6206
			317.2	0.7821
CO_2 - Air	3.7689	141.83	276.2	0.1325
			317.2	0.1709
A - He	2.9992	37.0	276.2	0.6369
			317.2	0.8031
CO_2 - He	3.2589	46.25	276.2	0.5174
			317.2	0.6539
CO_2 - A	3.6721	160	276.2	0.1220
			317.2	0.1578
A - Air	3.5092	113.42	276.2	0.1677
			317.2	0.2145

TABLE V(b)

Calculated Diffusion Coefficients for Binary Gas Mixtures at 1 Atmosphere

Gas Pair	σ_{12} (Å)	ϵ_{12}/K (K)	T (K)	D_{12} ($cm^2\ sec^{-1}$)
A - O_2	3.439	118.7	293.2	0.1868
A - N_2	3.567	103.9	293.2	0.1879
A - H_2	3.1762	66.93	293.2	0.775
N_2- H_2	3.331	54.32	273.2	0.660
			288.2	0.724
N_2- O_2	3.5945	96.3	273.2	0.1761
			293.2	0.204
N_2- CO_2	3.826	129.9	273.2	0.1351
			298.2	0.158
H_2- O_2	3.2036	62.05	273.2	0.690
H_2- CO_2	3.436	83.67	273.2	0.551
			298.2	0.643
CO_2-O_2	3.699	148.22	273.2	0.129

SAMPLE CALCULATIONS

Calculation of the Gas Density. For experimental test number 1, the density of air was calculated as follows:

$$\rho = \rho_{(STP)} \times \frac{273.16}{T} \times \frac{P}{760.0}$$

where $\rho_{(STP)} = 1.293$ gm/liter

$T = 298.16\ ^{o}K$

$P = 736.0$ mm Hg

so

$$\rho = (1.293)\ \frac{(273.16)\ (736.0)}{(298.16)\ (760.0)} = 1.146 \text{ gm/liter}$$

Calculation of the Tube Inclination Angle. For experimental test number 3, the angle of inclination of the viscometer tube was calculated as follows:

$$\sin\theta = \frac{\text{Elevation of the board}}{\text{length of the board}} = \frac{8.06 \text{ cm}}{76.605 \text{ cm}}$$

$$\sin\theta = 0.1044$$

$$\theta = 5^{o}59'$$

Calculation of the Resistance Factor. For experimental test number 5, the resistance factor was calculated as follows:

$$\text{Resistance factor} = \frac{5\pi g}{42} \times \frac{(D+d)^2}{L^2 d} \times \frac{\rho_o - \rho}{\rho} \times Z^2 \sin\theta$$

where $g = 980$ cm/sec/sec

$D = 1.270$ cm

$d = 1.2608$ cm

$L = 45.65$

$\rho_o = 7{,}807$ gm/liter

$\rho = 1.141$ gm/liter

$Z = 17.41$ sec

$\sin \theta = 0.1575$

$$\text{Resistance factor} = \frac{5\pi \times 980}{42} \times \frac{(1.270+1.2608)^2}{45.65^2 \times 1.2608} \times$$

$$\frac{7807-1.141}{1.141} \times 17.41^2 \times 0.1575$$

Resistance factor = 28,400

Calculation of the Reynold's Number. For experimental test number 5, the Reynold's number was calculated as follows:

$$\text{Reynold's Number} = \frac{Ld^2}{(D+d)} \times \frac{\rho}{\mu Z}$$

where $L = 45.65$ cm

$d = 1.2608$ cm

$D = 1.270$ cm

$\rho = 1.141$ gm/liter

$\mu = 1{,}834 \times 10^{-7}$ gm/cm-sec

$Z = 17.41$ sec

then

$$\text{Reynold's number} = \frac{45.65\ (1.2608)^2}{(1.2608+1.27)} = \frac{1.141}{17.41 \times 1,834 \times 10^{-7}}$$

$$\text{Reynold's number} = 10.02$$

Calculation of the Gas Viscosity. For experiment test number 41, the viscosity of argon was calculated as follows:

$$\frac{\mu_{air}}{\mu_A} = \frac{Z_{air}}{Z_A} \qquad (19)$$

or $$\mu_A = \frac{Z_A}{Z_{air}} \times \mu_{air}$$

where $\mu_{air} = 1,741 \times 10^{-7}$ gm/cm-sec (5^oC)

$Z_{air} = 17.02$ sec

$Z_A = 20.69$ sec

so the viscosity of argon at 5^oC

$$\mu_A = \frac{20.69}{17.02} \times 1,741 \times 10^{-7} = 2,116 \times 10^{-7} \text{ gm/cm-sec}$$

Calculation of the Force Constant (ε/K). The force constant (ε/K) for argon between the temperatures 5 and 90 degree centigrade was calculated as follows:

$$\frac{\mu(T_2)}{\mu(T_1)} \frac{T_1}{T_2}^{0.5} = \frac{\Omega^{(2)}(T_1^*)}{\Omega^{(2)}(T_2^*)} \frac{f_\mu^{(3)}(T_2^*)}{f_\mu^{(3)}(T_1^*)} \qquad (25)$$

where $\mu(T_1) = 2{,}116 \times 10^{-7}$ gm/cm - sec

$\mu(T_2) = 2{,}625 \times 10^{-7}$ gm/cm - sec

$T_1 = 278.16\ ^{o}K$

$T_2 = 363.16\ ^{o}K$

The calculation is a trial and error solution. Assume that the value of (ϵ/K) for argon was 128 ^{o}K. Thus:

$$T_1^* = \frac{278.16}{128} = 2.171$$

$$T_2^* = \frac{363.16}{128} = 2.8363$$

From the tables in Hirschfelder, Curtiss and Bird [3, 4] the following values for the collision integrals were obtained:

$$\Omega^{(2)}(T_1^*) = 1.1434$$

$$\Omega^{(2)}(T_2^*) = 1.0544$$

$$f_\mu^{(3)}(T_1^*) = 1.00178$$

$$f_\mu^{(3)}(T_2^*) = 1.00313$$

Since the right hand side of Equation (25) was:

$$\left[\frac{1.1434}{1.0544}\right]\left[\frac{1.00313}{1.00178}\right] = 1.0858$$

and the left hand side of Equation (25) was:

$$\left[\frac{2{,}625 \times 10^{-7}}{2{,}116 \times 10^{-7}}\right]\left[\frac{278.16}{363.16}\right]^{1/2} = 1.0856$$

The force constant (ϵ/K) for argon was 128 ^{o}K.

Calculation of the Collision Diameter. Once the value of (ϵ/K) is known, the collision diameter may be evaluated as follows:

$$\sigma^2 = \frac{266.93 \sqrt{M T_1} \left[f_\mu^{(3)}(T_1^*)\right]}{\left[\mu(T_1) \times 10^7\right] \Omega^{(2)}(T_1^*)} \qquad (26)$$

The collision diameter for argon was calculated by substituting the following values into above equation:

$M = 39.94$ gm

$\epsilon/K = 128\ ^oK$

$T_1^* = 2.171$

$f_\mu^{(3)}(T_1^*) = 1.00178$

$\Omega^{(2)}(T_1^*) = 1.1434$

$\mu(T_1^*) = 2{,}116 \times 10^{-7}$ gm/cm - sec

$$\sigma^2 = \frac{266.93 \sqrt{39.9 \times 278.16} \times 1.00178}{2{,}116 \times 1.1434} = 11.643$$

$\sigma = 3.4123\ \text{Å}$

Calculation of the Viscosity from the Force Constants. The viscosity of argon at 1500 ^oK was calculated from its force constant (ϵ/K) as follows:

$$\mu \times 10^7 = \frac{266.93 \sqrt{M T} \left[f_\mu^{(3)}(T^*)\right]}{\sigma^2 \Omega^{(2)}(T^*)} \qquad (10)$$

where $M = 39.94$ gm

$T = 1{,}500\ ^oK$

$\sigma = 3.4123\ \text{Å}$

$$T^* = \frac{1500}{128} = 11.719$$

$$f_\mu^{(3)}(T^*) = 1.0075$$

$$\Omega^{(2)}(T^*) = 0.81028$$

$$\mu = \frac{266.93 \sqrt{39.94 \times 1,500} \times 1.0075}{3.4123^2 \times 0.81028}$$

$$\mu = 6,973 \times 10^{-7} \text{ gm/cm - sec}$$

Calculation of Self-diffusion Coefficient from the Force Constants. The self-diffusion coefficient for nitrogen at 353.2 ^oK and one atmosphere was calculated from its force constants ϵ/K and σ as follows:

$$D = \frac{0.002628 \sqrt{T^3/M} \cdot f_D^{(3)}(T^*)}{\sigma^2 \Omega^{(1)}(T^*)} \qquad (11)$$

where $P = 1$ atmosphere

$M = 28.02$ gm

$T = 353.2\ ^oK$

$\epsilon/K = 84.3\ ^oK$

$\sigma = 3.722\ \text{Å}$

$$T^* = \frac{353.2}{84.3} = 4.19$$

$$\Omega^{(1)}(T^*) = 0.8745$$

$$f_D^{(3)}(T^*) = 1.005$$

$$D = \frac{0.002628 \sqrt{353.2^3/28.02} \times 1.005}{(1) \times (3.722)^2 \times 0.8745}$$

$$D = 0.2733 \text{ cm}^2/\text{sec}$$

Calculation of the Diffusion Coefficient for a Binary Gas Mixture from the Force Constants. The diffusion coefficient for the gas pair A - O_2 at 293.2 °K and one atmosphere was calculated as follows:

$$D_{12} = \frac{0.002628\sqrt{T^3(M_1+M_2)/2M_1M_2}}{\sigma_{12}^2\,\Omega^{(1)}(T_{12}^*)}\,f_D^{(3)}(T_{12}^*) \qquad (13)$$

where M_1 = molecular weight of O_2 = 32.0 gm

M_2 = molecular weight of A = 39.94 gm

P = 1 atmosphere

σ_{12} = 1/2 (3.467 + 3.4123) = 3.4396 Å

T = 293.2 °K

ϵ/K = $(128 \times 110)^{1/2}$ = 118.7 °K

T_{12}^* = $\frac{293.2}{118.7}$ = 2.47

$\Omega^{(1)}(T_{12}^*)$ = 1.0036

$f_D^{(3)}(T_{12}^*)$ = 1.0026

then

$$D = \frac{0.002628\sqrt{293.2^3(32.0+39.94)/2X32.0X39.94X1.0026}}{(1) \times (3.4396)^2 \times 1.0036}$$

$$= 0.1868 \text{ cm}^2/\text{sec}$$

IV. DISCUSSION

The discussion section of this thesis will be concerned with the following items: (1) discussion of results, (2) recommendations, and (3) limitations.

Discussions of Results

The discussion section of this thesis is divided into the following items: (1) comparison of experimental gas viscosities with previous investigations, (2) comparison of experimentally determined force constants with previous investigations, and (3) comparison of transport coefficients calculated from these force constants with the experimental data given in the literature.

Comparison of Experimental Gas Viscosities with Previous Investigations. The viscosities measured by the rolling ball viscometer for argon, helium, carbon dioxide, oxygen, hydrogen and nitrogen were found to be in good agreement with values given in the literature. Tables VI to XI inclusive compare the viscosities for the gases determined in this investigation with published viscosity values obtained from literature sources. (17, 18, 19) Viscosity data are also compared graphically with the accepted published data as shown in Figures 9 to 14 inclusive. The experimental viscosities for the six

TABLE VI

Comparison of the Experimental Values for the Viscosity of Argon with Previous Investigations

Temperature (°C)	Viscosity Experimental $\times 10^7$ (gm/cm-sec)	Viscosity by Previous (17, 18) Investigations $\times 10^7$ (gm/cm-sec)
5.0	2,116 $\pm$ 6.6	2,130
50.0	2,393 $\pm$ 6.2	2,405
90.0	2,625 $\pm$ 6.7	2,638

TABLE VII

Comparison of the Experimental Values for the Viscosity of Helium with Previous Investigations

Temperature (°C)	Viscosity Experimental $x10^7$ (gm/cm-sec)	Viscosity by Previous (17,18) Investigations $x10^7$ (gm/cm-sec)
5.0	1,869 ± 6.1	1,880
50.0	2,064 ± 5.8	2,080
90.0	2,223 ± 6.7	2,240

TABLE VIII

Comparison of the Experimental Values for the Viscosity of Carbon Dioxide with Previous Investigations

Temperature (°C)	Viscosity Experimental $\times 10^7$ (gm/cm-sec)	Viscosity by Previous (18, 19) Investigations $\times 10^7$ (gm/cm-sec)
5.0	1,417 ± 5.1	1,400
50.0	1,617 ± 5.5	1,630
90.0	1,806 ± 5.3	1,814

TABLE IX

Comparison of the Experimental Values for the Viscosity of Oxygen with Previous Investigations

Temperature (°C)	Viscosity Experimental $x10^7$ (gm/cm-sec)	Viscosity by Previous (18, 19) Investigations $x10^7$ (gm/cm-sec)
5.0	1,927 ± 7.3	1,943
50.0	2,168 ± 7.5	2,181
90.0	2,370 ± 10.3	2,380

TABLE X

Comparison of the Experimental Values for the Viscosity of Hydrogen with Previous Investigations

Temperature (°C)	Viscosity Experimental $\times 10^7$ (gm/cm-sec)	Viscosity by Previous (18, 19) Investigations 10^7 (gm/cm-sec)
5.0	862 $\pm$ 3.2	852
50.0	950 $\pm$ 4.5	939
90.0	1,025 $\pm$ 5.0	1010

TABLE XI

Comparison of the Experimental Values for the Viscosity of Nitrogen with Previous Investigations

Temperature (°C)	Viscosity Experimental $\times 10^7$ (gm/cm-sec)	Viscosity by Previous (18, 19) Investigations $\times 10^7$ (gm/cm-sec)
5.0	1,684 ± 6.8	1,680
50.0	1,880 ± 6.5	1,890
90.0	2,046 ± 10	2,065

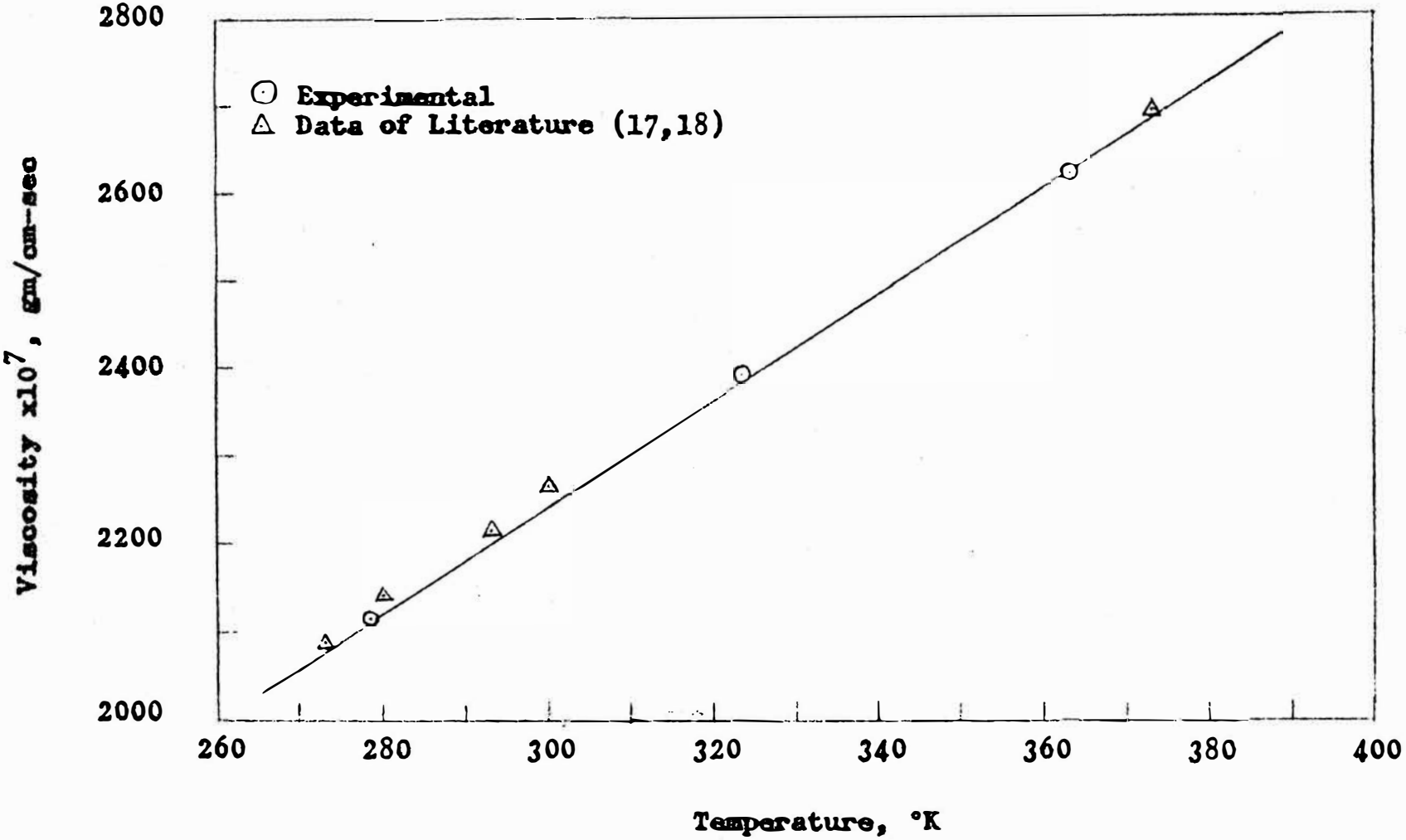

Figure 9. Viscosity Curve for Argon.

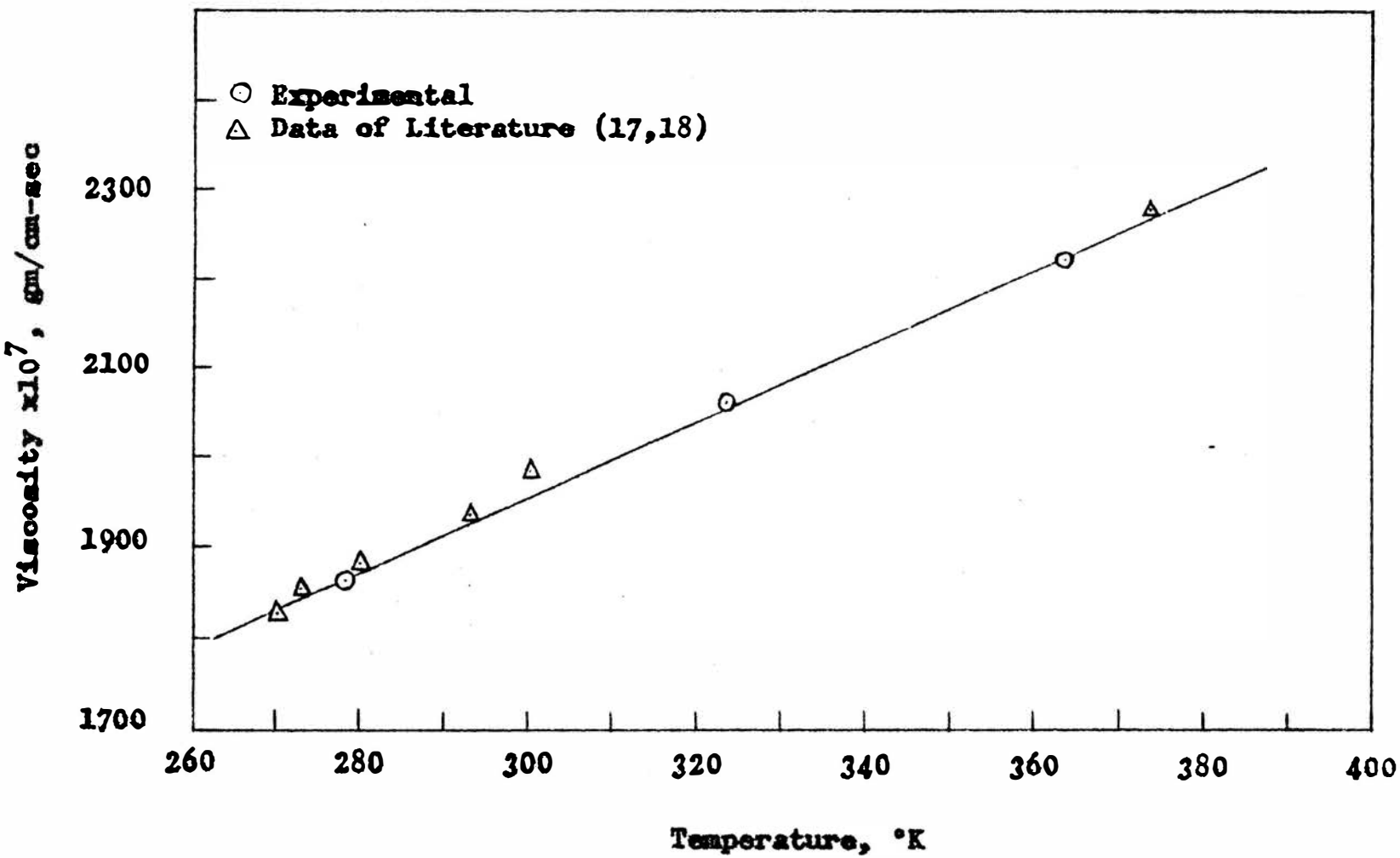

Figure 10. Viscosity Curve for Helium.

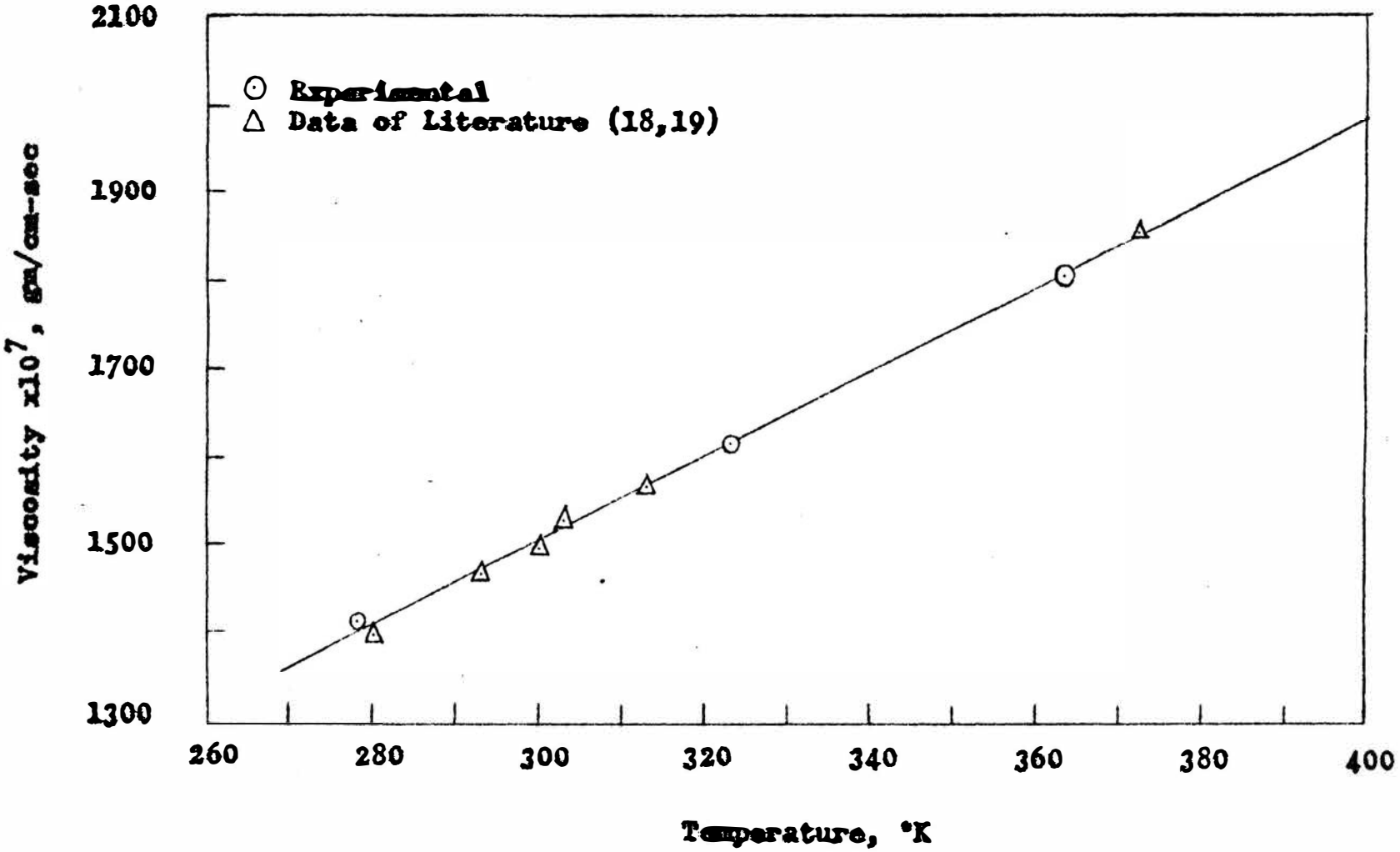

Figure 11. Viscosity Curve for Carbon Dioxide.

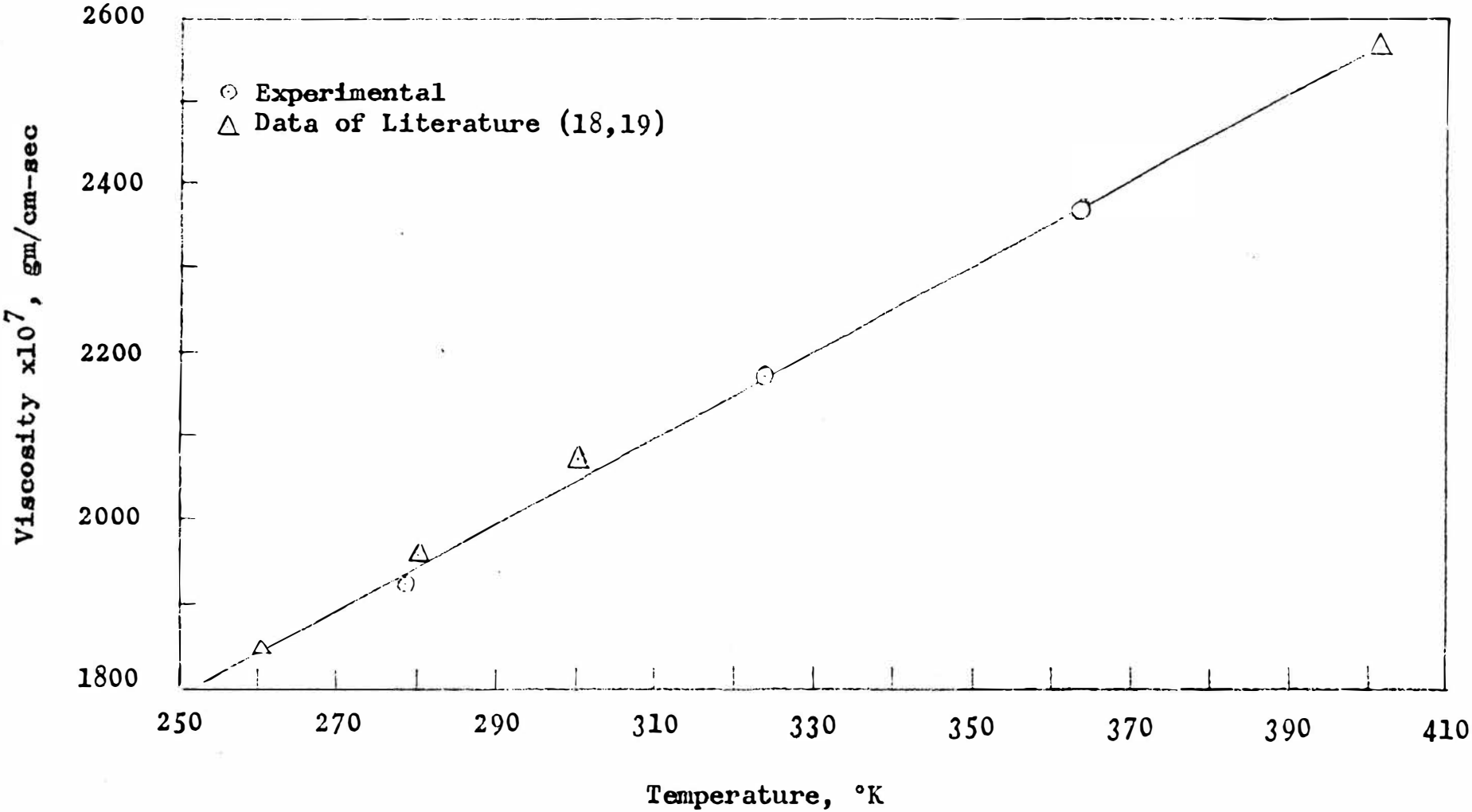

Figure 12. Viscosity Curve for Oxygen.

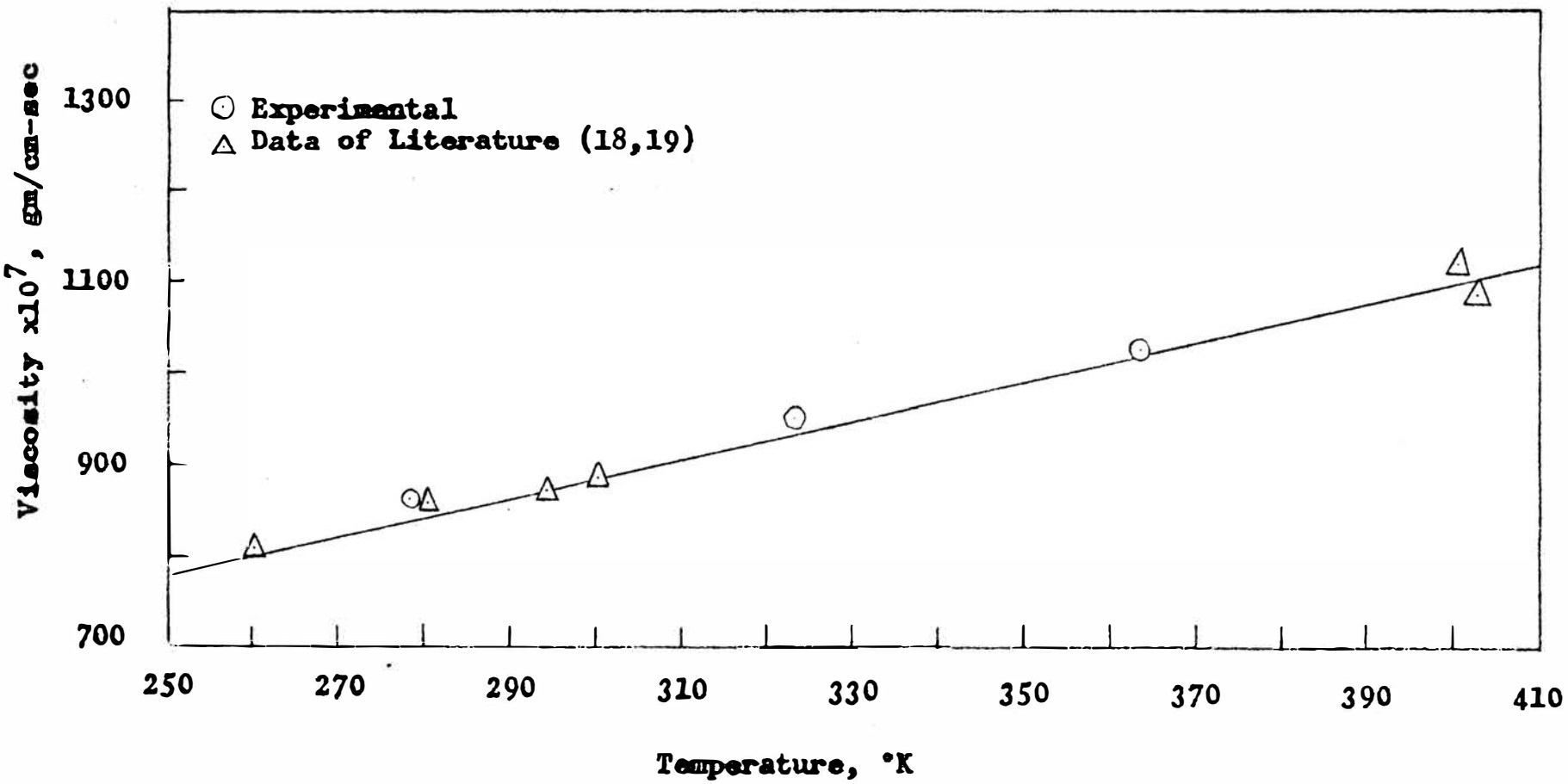

Figure 13. Viscosity Curve for Hydrogen.

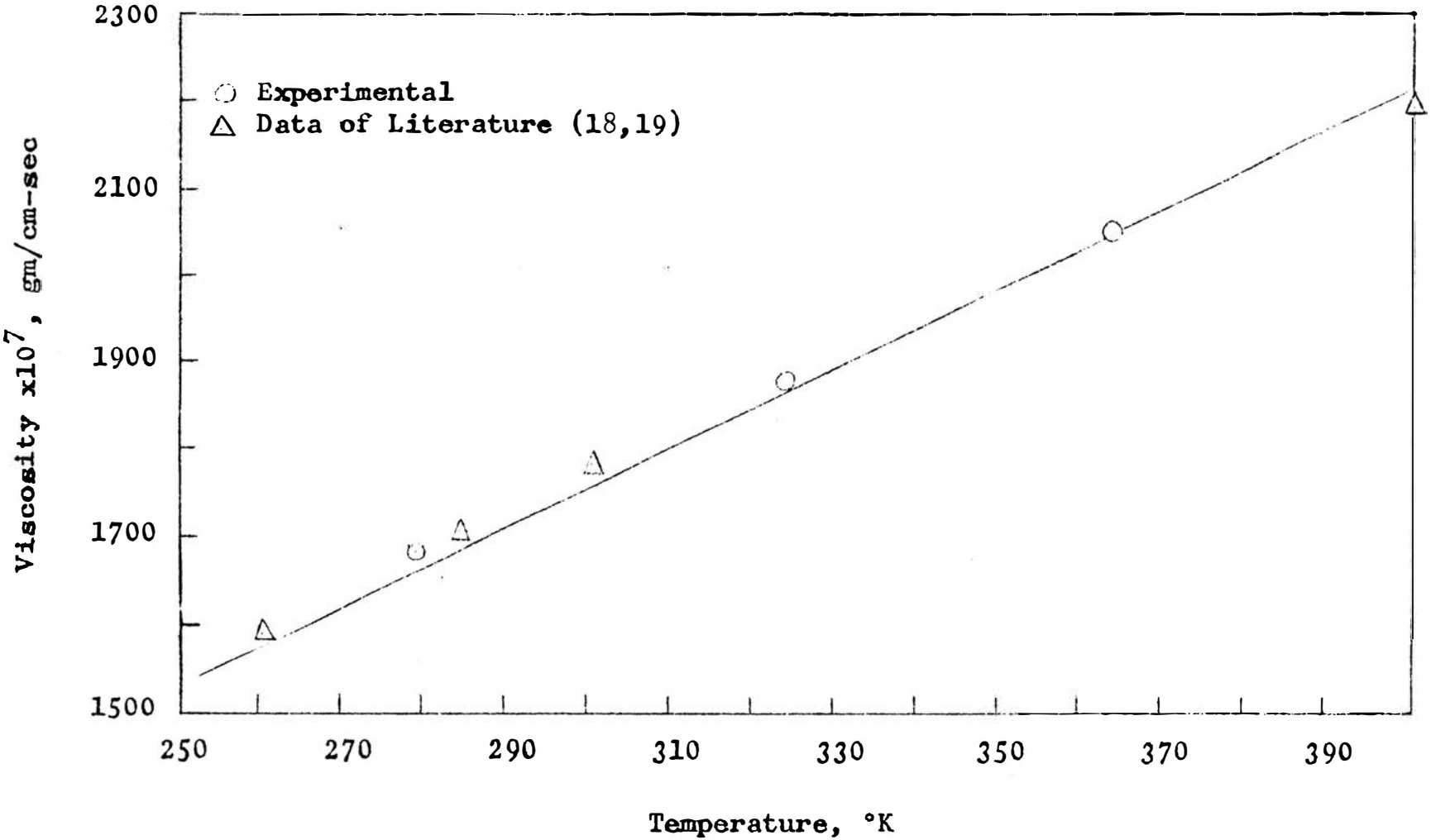

Figure 14. Viscosity Curve for Nitrogen.

selected non-polar gases were found to be within one and half per cent of those given in the literature. The accuracy of the experimental viscosity data are attributed to the fact that all of the measurements at a given temperature level were performed at constant inclination angles. Hence, for a given temperature the viscosity was dependent only upon the time required for the ball to roll a given distance in the viscometer. The time was accurately measured by using a photoelectric timing system.

Comparison of Experimentally Determined Force Constants with Previous Investigations. The values of the experimentally determined force constants were found to differ from values reported by previous investigators.[20] Table XII presents the values of the force constants for the Lennard-Jones potential calculated from the experimental viscosity data between 5 and 50 degrees Centigrade and compared with results from other investigations.

The force constants determined in this work varied somewhat from literature values. They varied from approximately three per cent for carbon dioxide to ten per cent for helium. This was attributed to the small variation in the experimental viscosity data since the values of the force constants are extremely sensitive to variations in viscosity data. None of the previous investigators

TABLE XII

Comparison of Force Constants from Experimental Data with Values from Previous Investigations

Gas	Force Constants Experimental		Force Constants Previous Investigations (20)	
Air	ϵ/K (^{o}K)	100.5	97	84
*	σ (Å)	3.606	3.617	3.689
Argon	ϵ/K	128 ± 5	124	116
	σ	3.4123	3.48	3.465
Helium	ϵ/K	10.7 ± 1.1	10.22	
	σ	2.5865	2.576	
Oxygen	ϵ/K	110 ± 7.5	113	88
	σ	3.467	3.433	3.541
Nitrogen	ϵ/K	84.3 ± 6.9	91.5	79.8
	σ	3.722	3.681	3.759
Hydrogen	ϵ/K	35 ± 3.05	33.3	38.0
	σ	2.9402	2.968	2.915
Carbon Dioxide	ϵ/K	200 ± 6	190	213
	σ	3.9319	3.996	3.897

* The force constants of air were calculated from the published viscosity data.

had given any information about the variation in the values of their force constants. Table II also lists the force constants for each gas evaluated from the viscosity data between 5 and 50, and 50 and 90 degrees Centigrade respectively. These data show that the magnitude of the force constants for argon, carbon dioxide, oxygen, hydrogen and nitrogen are nearly independent of the temperature range over which the force constants had been evaluated. This would indicate that the Lennard-Jones potential function is very satisfactory in explaining the intermolecular forces for these single non-polar gases. It was also observed that the force constants for helium varied somewhat over the range of temperature. This dependance of temperature for helium is probably due to the fact that the twelfth-power exponent on the repulsion term does not apply as well for helium as for the other gases. This also implies that the Lennard-Jones potential function is not entirely satisfactory for helium.

Comparison of Calculated Transport Coefficients with the Experimental Data Given in the Literature. The viscosities and the coefficients of diffusion for the six non-polar gases were calculated at various temperatures from their force constants. Table XIII lists the calculated viscosities at high temperatures where the viscosity could not be measured experimentally by the rolling

TABLE XIII(a)

Comparison of Calculated and Experimental [18,21]

Viscosities at High Temperatures

$x10^7$ in gm/cm-sec

T	A		He		CO_2	
(^oK)	Calcd.	Exptl.	Calcd.	Exptl.	Calcd.	Exptl.
500	3,337	3,345	2,736	2,763	2,350	2,385
800	4,629	4,621	3,709	3,840	3,356	3,567 3,391
1,000	5,370	5,302	4,285	4,455	3,930	3,935 4,198
1,200	6,071	5,947	4,795	-----	4,450	4,453 4,766
1,500	6,973	6,778	5,506	-----	5,170	5,139 5,529

TABLE XIII(b)

Comparison of Calculated and Experimental [18,21]

Viscosities at High Temperatures

$x10^7$ in gm/cm-sec

T	O_2		H_2		N_2	
(^oK)	Calcd.	Exptl.	Calcd.	Exptl.	Calcd.	Exptl.
500	2,990	3,017	1,251	1,257	2,554	2,560
800	4,120	4,273 4,115	1,709	1,744	3,498	3,610 3,493
1,000	4,781	4,917 4,720	1,976	1,987	4,016	4,066 4,011
1,200	5,366	5,492	2,223	2,205	4,506	4,613 4,452
1,500	5,967	6,264	2,569	2,496	5,225	5,050 5,247

TABLE XIV(a)

Comparison of Calculated and Experimental[22]

Diffusion Coefficients at 1 Atmosphere

Gas Pair	σ_{12} (Å)	ε_{12}/K (°K)	T (°K)	Calcd. D_{12} (cm^2/sec)	Exptl. D_{12} (cm^2/sec)
He - Air	3.096	32.79	276.2	0.6206	0.6242
			317.2	0.7821	0.7652
CO_2 - Air	3.7689	141.83	276.2	0.1325	0.1420
			317.2	0.1709	0.1772
A - He	2.9992	37.0	276.2	0.6369	0.6460
			317.2	0.8031	0.7968
CO_2 - He	3.2589	46.25	276.2	0.5174	0.5312
			317.2	0.6539	0.6607
CO_2 - A	3.6721	160	276.2	0.1220	0.1326
			317.2	0.1578	0.1652
A - Air	3.5092	113.42	276.2	0.1677	- - -
			317.2	0.2145	

TABLE XIV(b)

Comparison of Calculated and Experimental[23] Diffusion Coefficients at 1 Atmosphere

Gas Pair	σ_{12} (Å)	$\epsilon_{12/K}$ (°K)	T (°K)	Calcd. D_{12} (cm^2/sec)	Exptl. D_{12} (cm^2/sec)
A - O_2	3.439	118.7	293.2	0.1868	0.20
A - N_2	3.567	103.9	293.2	0.1879	0.20
A - H_2	3.1762	66.93	293.2	0.775	0.77
N_2 - H_2	3.331	54.32	273.2	0.660	0.674
			288.2	0.724	0.743
N_2 - O_2	3.5945	96.3	273.2	0.1761	0.181
			293.2	0.204	0.22
N_2 - CO_2	3.826	129.9	273.2	0.1351	0.144
			298.2	0.158	0.165
H_2 - O_2	3.2036	62.05	273.2	0.690	0.697
H_2 - CO_2	3.436	83.67	273.2	0.551	0.55
			298.2	0.643	0.646
CO_2 - O_2	3.699	148.22	273.2	0.129	0.139

TABLE XV

Comparison of Calculated and Observed [24] Self-Diffusion Coefficients at 1 Atmosphere

Gas	T (^{o}K)	D (cm^2sec)	D Experimental (cm^2/sec)
A	353.2	0.247	0.249
	273.2	0.156	0.158
	77.7	0.01335	0.0134
H_2	273	1.255	1.285
	85	0.1683	0.172
N_2	353.2	0.274	0.287
	273.2	0.175	0.172
	77.7	0.0163	0.0168
O_2	353.2	0.2785	0.301
	273.2	0.174	0.175
	77.7	0.0154	0.0153
CO_2	362.6	0.156	0.1644
	273.2	0.0915	0.0970
	194.8	0.0475	0.0516

ball viscometer. There is an excellent agreement between the calculated viscosities and the experimental viscosity data available in literature. The coefficients of diffusion for gas pairs and the self-diffusion coefficients for each gas at various temperatures and one atmosphere were also calculated from the force constants. They are also in very good agreement with the published experimental data as shown in Table XIV and Table XV.

Recommendations.

For future work the following recommendations are made:

1. Two different type photoelectric receivers with different sensitivities were used in the rolling ball viscometer. This could affect the reproducibility of the roll time readings. It is recommended that the Warner 62-R type photoelectric receiver should be replaced by another Warner 4000-R type photoelectric receiver, so a more precise time reading can be obtained.

2. It was found difficult to move the ball from the lower end to the upper end of the viscometer tube by using the magnet when the viscometer was operated at higher temperatures. This was due to the increased viscosity of the gas and the expansion of the steel ball

with increasing temperature. A steel ball with smaller diameter should be used for the high temperature viscosity measurements. It is also suggested that a more powerful permanent magnet be used to position the steel ball.

3. The highest operating temperature that could be reached by the water bath was 95 degrees Centigrade. If a colorless non-reactive liquid with a high boiling point could be used in the constant temperature bath, the viscometer would be capable of measuring the viscosity of a gas at a higher temperature.

Limitations.

The experimental work presented in this thesis was limited to the measurement of the viscosity and calculation of the force constants and other transport coefficients for argon, helium, carbon dioxide, oxygen, hydrogen and nitrogen. All the viscosity determinations were performed at 5, 50 and 90 degrees Centigrade and with a pressure of approximately one atmosphere. All experimental determinations were made with the tube filled with the pure gas. No determinations of the viscosity of mixtures were attempted in this work.

V. CONCLUSION

The determination of the force constants for the six selected non-polar gases from viscosity data measured with a rolling ball viscometer and the calculation of their transport coefficients at various temperatures led to the following conclusions:

1. The viscosity of any non-corrosive gas could be measured by this simple rolling ball viscometer satisfactorily within the temperature and pressure ranges used in this work.

2. The viscosity measured by this viscometer is essentially identical to the viscosity obtained under flow or other dynamic conditions.

3. The force constants for non-polar gases, which are in fairly good agreement with those given in the literature, could be evaluated from the viscosity data obtained in the limited temperature range from 5 to 90 degrees Centigrade.

4. The viscosity for each non-polar gas, the coefficient for self diffusion and diffusivities for non-polar gas pairs could be calculated from the force constants. These calculated values were in good agreement with experimental data.

5. It can be concluded that this rolling ball viscometer is suitable for carrying out further work for the viscosity measurements and the determination of force constants for non-polar gas mixtures.

VI. SUMMARY

The force constants for the non-polar gases argon, helium, carbon dioxide, oxygen, hydrogen and nitrogen were evaluated from the experimental viscosity data over a temperature range of 5 to 90 degrees Centigrade. A simple rolling ball viscometer was designed and constructed to determine the viscosity data for these non-polar gases. In this viscometer, a steel ball of known diameter was allowed to roll through an inclined precision bore glass tube. The viscosity of the gases could be determined accurately from the time required for the ball to traverse a specific distance in the viscometer tube which contained the gas to be studied. The viscosity of air was chosen to standardize this viscometer at each temperature. The time for the ball to traverse the specific distance in the viscometer tube was measured using a photoelectric timing system. The viscosity measurements were performed at a constant inclination angle for each particular temperature. The force constants for each non-polar gas were calculated from the experimental viscosity data using the Lennard-Jones potential energy function. The transport coefficients (viscosity and diffusion coefficients) at various temperatures were also calculated from these force constants.

The values of the experimental viscosity data, the calculated force constants and the calculated transport coefficients for the non-polar gases obtained in this investigation were in very good agreement with those values given in the literature sources.

VII. APPENDICES

All materials used in the experimental work are listed and described in Appendix A. The data taken during the experimental determinations of the viscosity coefficients are listed in Appendix B.

APPENDIX A

List of Materials

Air. Compressed, oil pumped. Specifications: air 99.9 per cent, with 20.9 per cent oxygen, 79.1 per cent nitrogen, and 0.1 per cent argon. The dew point is -75 degrees Fahrenheit. Used for standardization medium in the viscometer.

Argon. Compressed. Specifications: Argon with minimum purity of 99.995 per cent containing less than 7 ppm of oxygen, 5 ppm of hydrogen and 50 ppm of nitrogen with a dew point around -90 degrees Fahrenheit.

Helium. Compressed. Specifications: Helium minimum purity 99.99 per cent with a dew point around -76 degrees Fahrenheit.

Carbon Dioxide. Compressed, Bone Dry. Specifications: Carbon Dioxide, Bone Dry with a minimum purity of 99.8 per cent with 0.05 per cent nitrogen, 0.009 per cent oxygen and 0.0025 per cent water.

Oxygen. Compressed, extra dry. Specifications: Oxygen with a minimum purity of 99.8 per cent with 0.1 per cent of carbon dioxide and 0.05 per cent of nitrogen.

Hydrogen. Compressed, Electrolytic Grade. Specification: Hydrogen with a minimum purity of 99.8 per cent

with 0.03 per cent nitrogen, 0.005 per cent carbon dioxide and 0.001 per cent water.

Nitrogen. Compressed, Research Grade. Specifications: Nitrogen with a minimum purity of 99.9 per cent containing less than 5 ppm of oxygen, 5 ppm of hydrogen and 50 ppm of argon.

All of the above gases were obtained from the Matheson Company, Inc., P. O. Box 966, Joliet, Illinois.

APPENDIX B

Experimental Data

This appendix contains the experimental data that was taken in this investigation.

TABLE XVI

Experimental Data for Determination of the Viscometer "Correlation Curve" Using Air at 25°C and Atmospheric Pressure

Test No.	Angle of Inclination (° ')		Viscosity $\times 10^7$ ($gm/cm\text{-}sec$)	Reynold's No.	Resistance Factor
1	3	57	1,834	4.35	686,000
2	5	36	1,834	6.27	467,000
3	5	59	1,834	6.78	431,000
4	7	8	1,834	7.85	380,000
5	9	4	1,834	10.02	284,000
6	11	13	1,834	11.87	260,500
7	12	4	1,834	13.65	211,000
8	12	43	1,834	14.11	207,000

TABLE XVII

Experimental Data for Standardization of the Viscometer Using Air at 5°C Atmospheric Pressure and 8°21' Inclination Angle

Test No.	Roll Time (sec)	Test No.	Roll Time (sec)
9	17.01	19	17.02
10	17.03	20	17.03
11	17.02	21	17.05
12	17.00	22	16.99
13	16.96	23	16.97
14	17.06	24	17.01
15	17.00	25	17.07
16	16.99	26	17.09
17	17.05	27	16.99
18	17.04	28	17.02

TABLE XVIII

Experimental Data for Determination of the Viscosity of Argon at 5°C, Atmospheric Pressure and 8°21' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
29	20.65	2,112.3	39	20.62	2,109.3
30	20.66	2,113.3	40	20.73	2,121.5
31	20.72	2,119.5	41	20.69	2,116.4
32	20.66	2,113.3	42	20.67	2,114.4
33	20.72	2,119.5	43	20.73	2,121.5
34	20.75	2,122.5	44	20.67	2,114.4
35	20.71	2,118.5	45	20.72	2,119.5
36	20.68	2,115.4	46	20.65	2,112.3
37	20.67	2,114.4	47	20.71	2,118.5
38	20.68	2,115.4	48	20.66	2,113.3

TABLE XIX

Experimental Data for Determination of the Viscosity of Helium at 5°C, Atmospheric Pressure and 8°21' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $x10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $x10^7$ (gm/cm-sec)
49	18.24	1,864.8	59	18.30	1,871.9
50	18.27	1,868.8	60	18.24	1,865.8
51	18.28	1,869.9	61	18.23	1,864.8
52	18.24	1,865.8	62	18.24	1,865.8
53	18.31	1,873.0	63	18.25	1,866.8
54	18.29	1,870.9	64	18.27	1,868.8
55	18.29	1,870.9	65	18.27	1,868.8
56	18.25	1,866.8	66	18.28	1,869.9
57	18.24	1,865.8	67	18.24	1,865.8
58	18.35	1,877.0	68	18.29	1,870.9

TABLE XX

Experimental Data for Determination of the Viscosity of Carbon Dioxide at 5°C, Atmospheric Pressure and 8°21' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
69	13.86	1,417.8	79	13.87	1,418.8
70	13.90	1,421.9	80	13.83	1,414.7
71	13.85	1,416.7	81	13.82	1,413.7
72	13.86	1,417.8	82	13.81	1,412.6
73	13.84	1,415.7	83	13.81	1,412.6
74	13.84	1,415.7	84	13.89	1,420.8
75	13.83	1,414.7	85	13.89	1,420.8
76	13.85	1,416.7	86	13.90	1,421.9
77	13.80	1,411.6	87	13.87	1,418.8
78	13.86	1,417.8	88	13.84	1,415.7

TABLE XXI

Experimental Data for Standardization of the Viscometer Using Air at 50°C, Atmospheric Pressure and 8°34' Inclination Angle

Test No.	Roll Time (sec)	Test No.	Roll Time (sec)
89	21.73	99	21.79
90	21.75	100	21.74
91	21.69	101	21.79
92	21.74	102	21.80
93	21.77	103	21.74
94	21.74	104	21.81
95	21.73	105	21.73
96	21.69	106	21.68
97	21.74	107	21.71
98	21.73	108	21.79

TABLE XXII

Experimental Data for Determination of the Viscosity of Argon at 50°C, Atmospheric Pressure and 8°34' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$
109	26.72	2,397.4	119	26.61	2,387.5
110	26.68	2,393.8	120	26.62	2,388.4
111	26.71	2,396.5	121	26.60	2,386.6
112	26.74	2,399.2	122	26.71	2,396.5
113	26.72	2,397.4	123	26.67	2,392.9
114	26.67	2,392.9	124	26.69	2,394.7
115	26.69	2,394.7	125	26.62	2,388.4
116	26.70	2,395.6	126	26.63	2,389.3
117	26.66	2,392.0	127	26.66	2,392.0
118	26.66	2,392.0	128	26.68	2,393.8

TABLE XXIII

Experimental Data for Determination of the Viscosity of Helium at 50°C, Atmospheric Pressure and 8°34' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
129	23.01	2,064.5	139	23.01	2,064.5
130	23.01	2,064.5	140	23.02	2,065.4
131	23.06	2,069.0	141	23.04	2,067.2
132	23.04	2,067.2	142	23.02	2,065.4
133	22.94	2,058.2	143	23.01	2,064.5
134	22.94	2,058.2	144	23.02	2,065.4
135	22.98	2,061.8	145	22.95	2,059.1
136	23.00	2,063.6	146	22.99	2,062.7
137	22.98	2,061.8	147	23.17	2,069.9
138	22.98	2,061.8	148	23.02	2,065.4

TABLE XXIV

Experimental Data for Determination of the Viscosity of Carbon Dioxide at 50°C, Atmospheric Pressure and 8°34' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
149	17.98	1,613.2	159	18.06	1,620.4
150	18.02	1,616.8	160	17.95	1,610.5
151	18.04	1,618.6	161	17.97	1,612.3
152	18.05	1,619.5	162	18.02	1,616.8
153	17.97	1,612.3	163	18.04	1,618.6
154	17.94	1,609.6	164	18.05	1,619.5
155	17.94	1,609.6	165	18.06	1,620.4
156	18.02	1,616.8	166	18.05	1,619.5
157	18.06	1,620.4	167	18.01	1,615.9
158	18.06	1,620.4	168	18.04	1,618.6

TABLE XXV

Experimental Data for Standardization of the Viscometer Using Air at 90°C, Atmospheric Pressure and 10°30' Inclination Angle

Test No.	Roll Time (sec)	Test No.	Roll Time (sec)
169	22.06	179	22.09
170	22.13	180	22.19
171	22.07	181	22.20
172	22.14	182	22.17
173	22.20	183	22.18
174	22.16	184	22.09
175	22.14	185	22.21
176	22.17	186	22.24
177	22.14	187	22.17
178	22.15	188	22.11

TABLE XXVI

Experimental Data for Determination of the Viscosity of Argon at 90°C, Atmospheric Pressure and 10°30' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
189	27.25	2,622.3	199	27.35	2,631.9
190	27.26	2,623.2	200	27.24	2,621.3
191	27.26	2,623.2	201	27.23	2,620.3
192	27.25	2,622.3	202	27.29	2,626.1
193	27.29	2,626.1	203	27.34	2,630.9
194	27.31	2,628.1	204	27.35	2,631.9
195	27.33	2,629.9	205	27.31	2,628.1
196	27.23	2,620.3	206	27.28	2,625.2
197	27.33	2,629.9	207	27.21	2,618.4
198	27.29	2,626.1	208	27.26	2,623.2

TABLE XXVII

Experimental Data for Determination of the Viscosity of Helium at 90°C, Atmospheric Pressure and 10°30' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
209	23.12	2,224.8	219	23.11	2,223.9
210	23.14	2,226.8	220	23.03	2,216.2
211	23.12	2,224.8	221	23.13	2,225.8
212	23.06	2,219.1	222	23.03	2,216.2
213	23.14	2,226.7	223	23.10	2,222.9
214	23.13	2,225.8	224	23.12	2,224.8
215	23.10	2,222.9	225	23.17	2,229.7
216	23.07	2,220.0	226	23.08	2,221.0
217	23.12	2,224.8	227	23.09	2,221.9
218	23.13	2,225.8	228	23.08	2,221.0

TABLE XXVIII

Experimental Data for Determination of the Viscosity of Carbon Dioxide at 90°C, Atmospheric Pressure and 10°30' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
229	18.74	1,803.4	239	18.80	1,809.1
230	18.75	1,804.3	240	18.78	1,807.2
231	18.78	1,807.2	241	18.80	1,809.1
232	18.76	1,805.3	242	18.75	1,804.3
233	18.74	1,803.4	243	18.76	1,805.3
234	18.72	1,801.4	244	18.82	1,811.1
235	18.75	1,804.3	245	18.75	1,804.3
236	18.83	1,812.0	246	18.74	1,803.4
237	18.79	1,808.2	247	18.75	1,804.3
238	18.79	1,808.2	248	18.82	1,811.1

TABLE XXIX

Experimental Data for Standardization of the Viscometer Using Air at 5°C, Atmospheric Pressure and 7°45' Inclination Angle

Test No.	Roll Time (sec)	Test No.	Roll Time (sec)
249	19.12	259	19.13
250	19.18	260	19.21
251	19.19	261	19.15
252	19.21	262	19.14
253	19.10	263	19.16
254	19.17	264	19.18
255	19.21	265	19.20
256	19.12	266	19.11
257	19.10	267	19.13
258	19.12	268	19.19

TABLE XXX

Experimental Data for Determination of the Viscosity of Oxygen at 5°C, Atmospheric Pressure and 7°45' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
269	21.25	1,931.3	279	21.24	1,930.4
270	21.21	1,927.7	280	21.15	1,922.2
271	21.27	1,933.2	281	21.18	1,925.0
272	21.12	1,919.5	282	21.19	1,925.9
273	21.25	1,931.3	283	21.25	1,931.3
274	21.17	1,924.0	284	21.22	1,928.6
275	21.21	1,927.7	285	21.25	1,931.3
276	21.17	1,924.0	286	21.22	1,928.6
277	21.25	1,931.3	287	21.18	1,925.0
278	21.09	1,916.8	288	21.21	1,927.7

TABLE XXXI

Experimental Data for Determination of the Viscosity of Nitrogen at 5°C, Atmospheric Pressure and 7°45' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
289	18.58	1,688.6	299	18.46	1,677.7
290	18.57	1,687.7	300	18.48	1,679.6
291	18.58	1,688.6	301	18.48	1,679.6
292	18.58	1,688.6	302	18.58	1,688.6
293	18.60	1,690.4	303	18.49	1,680.5
294	18.57	1,687.7	304	18.51	1,682.3
295	18.51	1,682.3	305	18.60	1,690.4
296	18.48	1,679.6	306	18.52	1,683.2
297	18.50	1,681.4	307	18.47	1,678.6
298	18.45	1,676.8	308	18.59	1,689.6

TABLE XXXII

Experimental Data for Determination of the Viscosity of Hydrogen at 5°C, Atmospheric Pressure and 7°45' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $x10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $x10^7$ (gm/cm-sec)
309	9.45	858.8	319	9.48	861.6
310	9.50	863.4	320	9.49	862.5
311	9.48	861.6	321	9.50	863.4
312	9.49	862.5	322	9.47	860.7
313	9.48	861.6	323	9.48	861.6
314	9.47	860.7	324	9.49	862.5
315	9.49	862.5	325	9.47	860.7
316	9.43	857.1	326	9.48	861.6
317	9.50	863.4	327	9.50	863.4
318	9.49	862.5	328	9.46	859.8

TABLE XXXIII

Experimental Data for Standardization of the Viscometer Using Air at 50°C, Atmospheric Pressure and 8°11' Inclination Angle

Test No.	Roll Time (sec)	Test No.	Roll Time (sec)
329	23.00	339	22.87
330	23.00	340	22.97
331	22.92	341	22.96
332	22.84	342	23.01
333	22.84	343	22.86
334	22.98	344	22.91
335	22.84	345	22.96
336	22.94	346	23.00
337	22.95	347	22.94
338	23.01	348	22.95

TABLE XXXIV

Experimental Data for Determination of the Viscosity of Oxygen at 50°C, Atmospheric Pressure and 8°11' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
349	25.40	2,160.5	359	25.40	2,160.5
350	25.57	2,175.0	360	25.48	2,167.3
351	25.49	2,168.2	361	25.53	2,171.6
352	25.47	2,166.5	362	25.57	2,175.0
353	25.47	2,166.5	363	25.50	2,169.0
354	25.48	2,167.3	364	25.39	2,159.7
355	25.55	2,173.3	365	25.39	2,159.7
356	25.50	2,169.0	366	25.43	2,163.1
357	25.57	2,175.0	367	25.53	2,171.6
358	25.48	2,167.3	368	25.44	2,163.9

TABLE XXXV

Experimental Data for Determination of the Viscosity of Nitrogen at 50°C, Atmospheric Pressure and 8°11' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
369	22.10	1,879.8	379	22.17	1,885.8
370	22.09	1,879.0	380	22.15	1,884.1
371	22.14	1,883.2	381	22.13	1,882.4
372	22.10	1,879.8	382	22.06	1,876.4
373	22.02	1,873.0	383	22.08	1,878.1
374	22.14	1,883.2	384	22.08	1,878.1
375	22.10	1,879.8	385	22.17	1,885.8
376	22.02	1,873.0	386	22.04	1,874.7
377	22.14	1,883.2	387	22.10	1,879.8
378	22.06	1,876.4	388	22.15	1,884.1

TABLE XXXVI

Experimental Data for Determination of the Viscosity of Hydrogen at 50°C, Atmospheric Pressure and 8°11' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
389	11.11	945.0	399	11.16	949.2
390	11.15	948.4	400	11.20	952.6
391	11.14	947.6	401	11.22	954.4
392	11.20	952.7	402	11.21	953.5
393	11.19	951.8	403	11.20	952.5
394	11.19	951.8	404	11.15	948.4
395	11.15	948.4	405	11.18	950.9
396	11.20	952.7	406	11.20	952.7
397	11.17	950.1	407	11.17	950.1
398	11.17	950.1	408	11.14	947.6

TABLE XXXVII

Experimental Data for Standardization of the Viscometer Using Air at 90°C, Atmospheric Pressure and 9°03' Inclination Angle

Test No.	Roll Time (sec)	Test No.	Roll Time (sec)
409	24.77	419	24.75
410	24.87	420	24.74
411	24.68	421	24.84
412	24.78	422	24.86
413	24.87	423	24.79
414	24.81	424	24.78
415	24.69	425	24.83
416	24.76	426	24.71
417	24.65	427	24.80
418	24.70	428	24.74

TABLE XXXVIII

Experimental Data for Determination of the Viscosity of Oxygen at 90°C, Atmospheric Pressure and 9°03' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
429	27.65	2,379.3	439	27.46	2,363.0
430	27.56	2,371.6	440	27.50	2,366.4
431	27.41	2,358.7	441	27.56	2,371.6
432	27.41	2,358.7	442	27.59	2,374.2
433	27.65	2,379.3	443	27.58	2,373.3
434	27.52	2,368.1	444	27.60	2,375.0
435	27.50	2,366.4	445	27.51	2,367.3
436	27.49	2,365.6	446	27.49	2,365.6
437	27.59	2,374.2	447	27.56	2,371.6
438	27.58	2,373.3	448	27.51	2,367.3

TABLE XXXIX

Experimental Data for Determination of the Viscosity of Nitrogen at 90°C, Atmospheric Pressure and 9°03' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
449	23.81	2,048.9	459	23.85	2,052.3
450	23.90	2,056.6	460	23.75	2,043.7
451	23.92	2,058.4	461	23.70	2,039.4
452	23.67	2,036.8	462	23.88	2,054.9
453	23.69	2,038.6	463	23.70	2,039.4
454	23.78	2,046.3	464	23.73	2,042.0
455	23.68	2,037.7	465	23.70	2,039.4
456	23.69	2,038.6	466	23.69	2,038.6
457	23.76	2,044.6	467	23.90	2,056.6
458	23.84	2,051.5	468	23.73	2,042.0

TABLE XL

Experimental Data for Determination of the Viscosity of Hydrogen at 90°C, Atmospheric Pressure and 9°03' Inclination Angle

Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)	Test No.	Roll Time (sec)	Viscosity $\times 10^7$ (gm/cm-sec)
469	11.91	1,024.9	479	11.94	1,027.5
470	11.90	1,024.0	480	11.94	1,027.5
471	11.89	1,023.1	481	11.92	1,025.7
472	11.84	1,018.9	482	11.86	1,020.6
473	11.85	1,019.7	483	11.92	1,025.7
474	11.96	1,029.2	484	11.84	1,018.9
475	11.90	1,024.0	485	11.89	1,023.1
476	11.96	1,029.2	486	11.94	1,027.5
477	11.95	1,028.3	487	11.95	1,038.3
478	11.96	1,029.2	488	11.90	1,024.0

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